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The 'ENGLISH ELECTRIC' Journal

VOLUME SIXTEEN • NUMBER SEVEN

SEPTEMBER 1960

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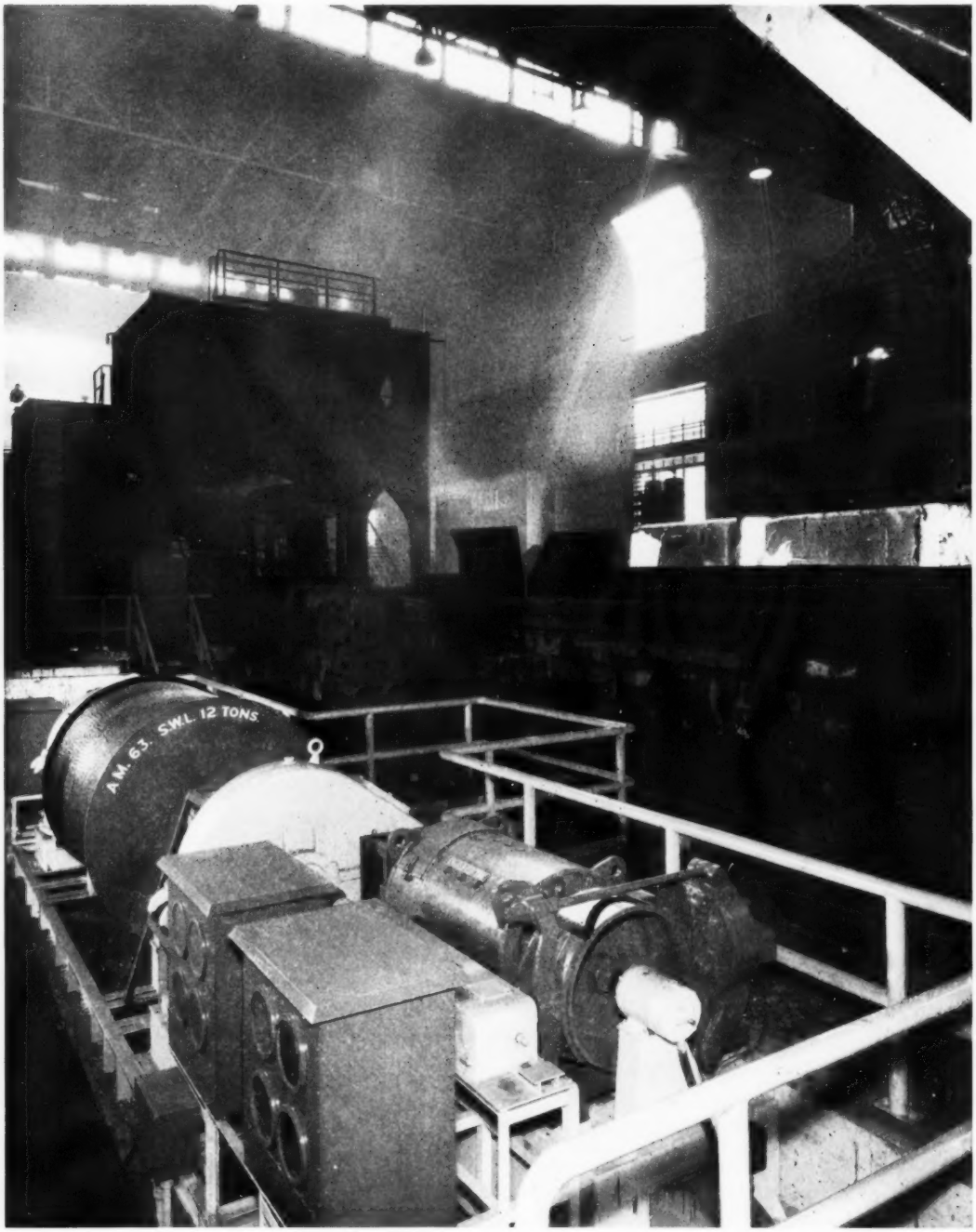
All communications respecting Editorial Contents should be addressed to the Editor, THE ENGLISH ELECTRIC JOURNAL, THE ENGLISH ELECTRIC COMPANY LIMITED, STAFFORD, ENGLAND.



Ingots being transferred from the shuttle car on to the table of the universal slabbing mill at the Port Talbot Works of the Steel Company of Wales. In the foreground is the electrically-controlled winch equipment that draws the shuttle car along the track from the ingot soaking pits to the mill table. (*See article on p.* 42).

Electrical Control Systems in Heavy Industry

by H. S. BROWN, B.Eng., M.I.E.E., Chief Engineer, Metal Industries Division,
and J. C. CHRISTIE, B.Sc., A.M.I.E.E., Chief Engineer, Mining Division.

This article is in all essentials a reproduction of the Paper presented by the authors to the South African Institute of Electrical Engineers on 22nd October, 1959.

INTRODUCTION

IN OCTOBER 1909 a paper was read in England in which a description was given of one of the first electrical reversing mill drives. In the ensuing discussion one of the speakers referred to the control circuits and stated that these seemed to him to be rather intricate arrangements to be introduced into steelworks, where the class of labour was not of the highest ; he thought that unless there were enormous advantages to be gained by the introduction of all this complication, owners of steelworks would be inclined to fight shy of these devices requiring really highly skilled labour to operate and supervise[1].

Such statements are still heard today. In 1909, however, they referred to a control system which by today's practice was extremely simple. In fact the speaker was concerned only with the method of over-load protection. Today the words refer to the complex systems associated with the automatic control of process units.

In the intervening years great progress has been made in control system design. In the next few decades very much greater progress will be made. Comments such as the above will be heard more often, not less. At the same time they will appear more justified in view of the increasing complexity in control systems, but this will be wrong. To industries carrying heavy capital overheads the improvements in operation that can arise from improved control systems offer the prospect of very significant improvements in cost and quality of product. Also, by correct design of the equipment, and the training of personnel, overall reliability will tend to be improved in future control systems, rather than reduced.

However, even though this is accepted in principle, decisions are not easy to make in practice. Because of the complexity of modern control systems the correct course of action to be taken in the case of individual units or plants is by no means clear. It was felt therefore that a review of the pattern of control system development and of some of the problems involved in modern control system design and operation would be of use to engineers who are now facing this problem, and of general interest to anyone concerned in heavy industry. A Golden Jubilee occasion was thought particularly appropriate for such a review.

The principles set out in the paper apply to all heavy industry and particularly the steel and the mining industries. The examples given have all been taken from the steel industry, because of the very great extent to which this industry depends on the type of control system here being considered.

Because ' feedback ' control is such an essential part of present-day system design and of development, much of the paper is concerned with this aspect. The principles of feedback control and examples of the more important basic electrical control systems are given. These examples show clearly how technical difficulties increase as the operator is moved further back in the chain of command and control.

Recent developments have been concerned with the control of several subsidiary systems and these developments, together with future expectations, are dealt with in the last section of the paper.

DEFINITION AND OBJECT

For the purposes of this paper, a control system is defined as an assembly of circuits, amplifiers and measuring and translating devices which receives the commands of a human operator, controls the process to meet these commands, and at the same time protects the equipment. The number of commands that the operator has to give to achieve a given result and the accuracy with which they are met are a function of the complexity of the control system.

The immediate object of different control systems varies greatly, but they all have the same fundamental purpose—to enable human operators with maximum effectiveness to achieve results through an organisation of active components.

The range of systems now in use is bewildering. Nevertheless, the basic functions they perform are relatively few, and the majority of these functions are fulfilled by even the simplest systems. In taking a general view of control systems this should be borne in mind. The following list of the main functions with examples shows how even simple systems may fill each one.

(*a*) To provide a means whereby the operator can give instructions to a unit of equipment or process. These instructions may be either qualitative or quantitative, or both. A master controller does this.

(*b*) To store knowledge of certain predetermined requirements for the satisfactory operation of the equipment and process. Acceleration relays are an example.

(*c*) To store knowledge required to guard the equipment against damage from itself and from mal-operation. Overload relays are an example.

(*d*) To measure the variables associated with the particular process. These include such variables as physical dimensions, time, electrical quantities, temperature, etc. A rotary limit switch is an example.

(*e*) To use (*a*), (*b*) and (*d*) to cause the instruction to be obeyed.

(*f*) To use (*b*) and (*c*) to protect the equipment from damage.

(*g*) To repeat certain of the measurements in a form which can be read by the operator, i.e., instrumentation.

(*h*) To anticipate certain conditions that are going to arise. One of the simplest examples of this is the action of a limit switch as a slow-down position device.

HISTORY

The first control systems, used many years before electrical drives were dreamed of, were merely means of enabling the operator to control the flow of power to a process or machine. Later, protective devices such as the governor were added. The first electrical control systems achieved the same objects and it was still left to the operator to vary the power to give the performance desired.

Fig. 1 shows the chain of command and control for the simple hand-operated armature rheostat form of control. The chain for the early scheme that was the subject of the discussion referred to in the Introduction was basically the same. As well as correctly rolling the piece of steel, the operator had to ensure that his control of the electric drive did not over-stress the equipment.

It was realised at a very early stage that leaving the control of power flow solely to the operator was not satisfactory for most drives and processes. An essential part of any control system, be it in a drive system or in the management of an organisation of human beings, is the feedback of the results being produced and the comparison of this with the requirements laid down. The major part of an operator's working time is engaged in receiving information from direct observation of the process and equipment, and from instruments and other devices giving such information. Fig. 1 illustrates this.

We have said that the object of a control system is to enable human operators to manage an organisation of active components with the maximum effectiveness. The more therefore a control system can feedback information within itself, compare it with known requirements and correctly act to put right any discrepancies, the more useful will that control system be. The fact that it can perform some functions better than the human operator greatly enhances its value, because it

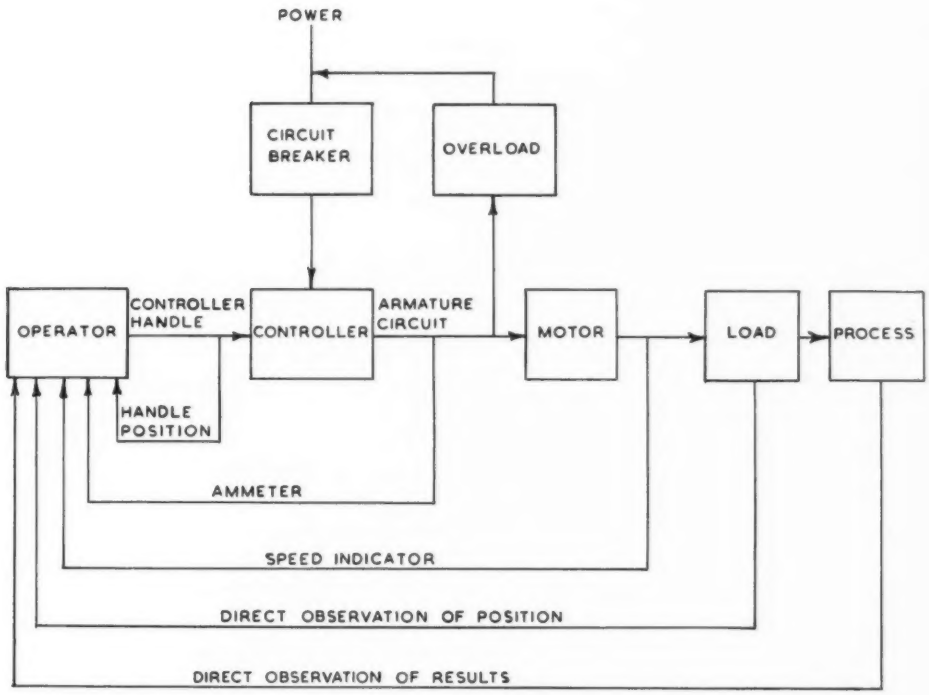


Fig. 1.—Chain of command and control for simple armature rheostat controller

often enables process methods to be adopted which would otherwise be impossible.

In the majority of process systems an operator is, in fact, controlling a number of subsidiary systems within the main process system. The first development is obviously to reduce the amount of feedback information which has to flow via the operator to control each subsidiary system satisfactorily—in other words, to move the operator further back in the chain of command and control, shown in Fig. 1. Very early in the development of electrical control systems simple circuits were introduced to do this, using load relays, position limit switches and similar devices to give a limited form of stepped feedback control. They were a great aid and they still meet the requirements of many drives. However, it was soon realised that much would be gained if the control system could monitor itself continuously. Early attempts at this failed because of the lack of amplifying devices and the lack of design techniques to enable the system performance to be correctly predicted.

For this reason control system development remained fairly static, except for component improvement, until the late 1930's. At that time the first rotating amplifiers were introduced and the feedback design techniques which had been developed in the radio field were adopted for industrial control. This opened the door to the development of closed loop feedback control systems, a development which has continued rapidly ever since. Parallel to this, considerable development has taken place in the components to meet the requirements of the new systems.

Without this development, many of our present industrial processes would not be possible. It is by its continuation that these processes will be improved. It is worth stressing that in most cases the more complicated control systems are introduced to satisfy a requirement which is external

to the electrical equipment. Whilst certain control features, such as current limit, are introduced to protect the electrical equipment, the majority of features (e.g., rapid response and accurate speed control) are incorporated to meet process requirements.

FEEDBACK CONTROL

There have been many excellent publications and papers on the problems of feedback control system design and it is not the object of this paper to cover this field. It is possible however, to highlight the main problems of the design and their solution, and this is done in the following section. A knowledge of the basic principles enables the details of the various types of control system to be appreciated.

Since the variable voltage drive is the system most familiar in industry, this will be used to illustrate these fundamentals, which it should be remembered apply to any form of continuous feedback control.

The principle of a feedback control system is that a proportion of the quantity to be regulated is fed back to oppose the initial actuating (or reference) signal, the difference between the two maintaining the desired output. This is represented diagrammatically in Fig. 2(*a*) and can be expressed as :

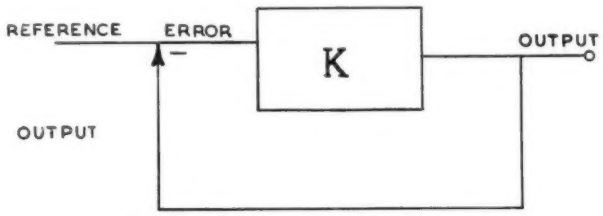
Reference − Output = Error

Error × Constant = Output

From the above it is seen that the relationship between the error and the output quantity has been assumed to be a constant (K in Fig. 2(*a*)). This however is not usually the case, since in most systems there are time delays or time constants caused by the inductance of components (e.g., machine fields), and the inertia of machines and the equipment they drive. These retard the signal as it passes through the various stages of a system. To illustrate this, if a voltage is suddenly applied to an inductive field the equation relating this voltage to the field current is transiently,

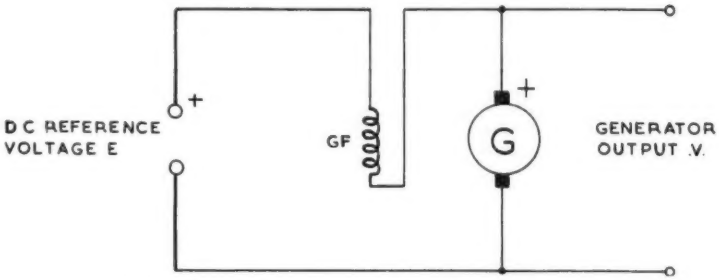
$$E = iR + Lpi,$$

where E = applied voltage, i = field current at any instant, R = field resistance, L = field inductance,



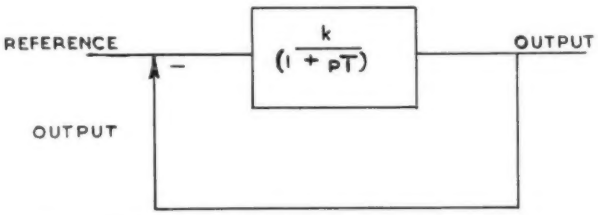
K = Relationship between output and input

Fig. 2(a)—Basic block diagram



G = Generator $\qquad$ $G.F.$ = Generator field

Fig. 2.(b)—Simple voltage control



k = Steady state relationship between output voltage of the machine and its field circuit voltage

p = Operator for $\frac{d}{dt}$ $\qquad$ $T = \frac{\text{Inductance}}{\text{Resistance}}$

Fig. 2.(c)—Block diagram of Fig. 2(b)

and p = operator for $\frac{d}{dt}$.

This can be written,

$$E = iR\left(1 + p\frac{L}{R}\right) \text{ or } iR\,(1 + pT),$$

where $T = \frac{\text{inductance}}{\text{resistance}}$ or the time constant of the field.

If the steady state relationship between the output voltage of a machine and its field current is, say, c then,

Output Voltage $= ci$, so that under transient conditions

$$\text{Output Voltage} = \frac{kE}{1 + pT} \text{ or } \frac{k \times \textit{Input}}{1 + pT},$$

where $k = \frac{c}{R}$

Thus the simple voltage control of Fig. 2(*b*) can be considered as the block diagram of Fig. 2(*c*). The effect of this is to make the former term K time-dependent, and the transfer function (as the term inside the block diagram is designated) becomes

$$\frac{k}{1 + pT}.$$

The three essential features of any closed loop scheme are (*a*) the accuracy, (*b*) the speed of response, and (*c*) the stability or damping, and before a satisfactory design can be concluded these factors have to be reconciled.

(*a*) *Accuracy*

It has been already established that under steady conditions the output voltage equals the input voltage multiplied by a constant k, and if the basic equations already mentioned are applied to the block diagram of Fig. 2(*c*) the following is obtained :—

$$(\text{Reference} - \text{Output})\frac{k}{1 + pT} = \text{Output}$$

so that the output/reference equals

$$\frac{k}{(1 + k)\left(1 + \frac{pT}{1 + k}\right)} \quad \ldots\ldots\ldots \text{ Equation 1.}$$

This means that if the output voltage has to be near in value to the reference, the closeness of the relationship (which is the accuracy) is fixed by $(1 + k)$. In this case $k\left(= \frac{c}{R}\right)$ is proportional to the slope of the open circuit characteristic of the generator as shown in Fig. 3(*a*) and is constant over the linear range of the machine.

(*b*) *Speed of Response*

If the reference voltage of the example is suddenly

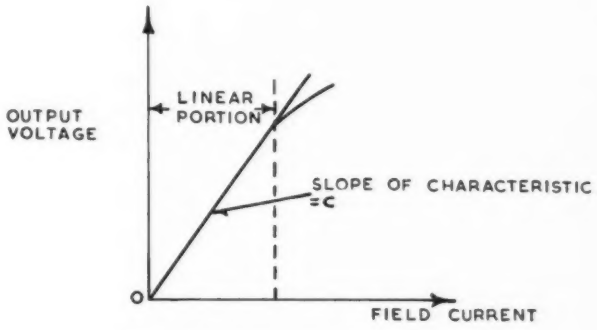


Fig. 3.(a)—Generator characteristic

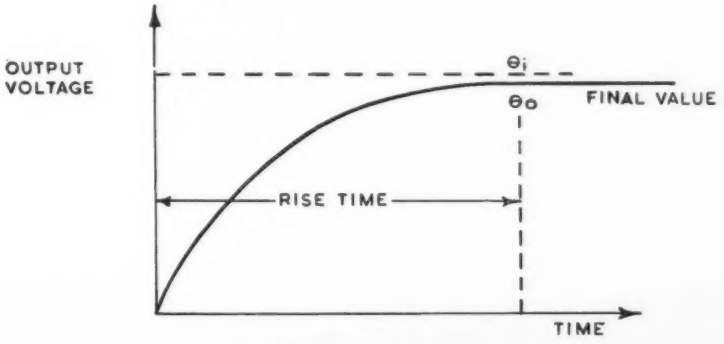


Fig. 3.(b)—Exponential response

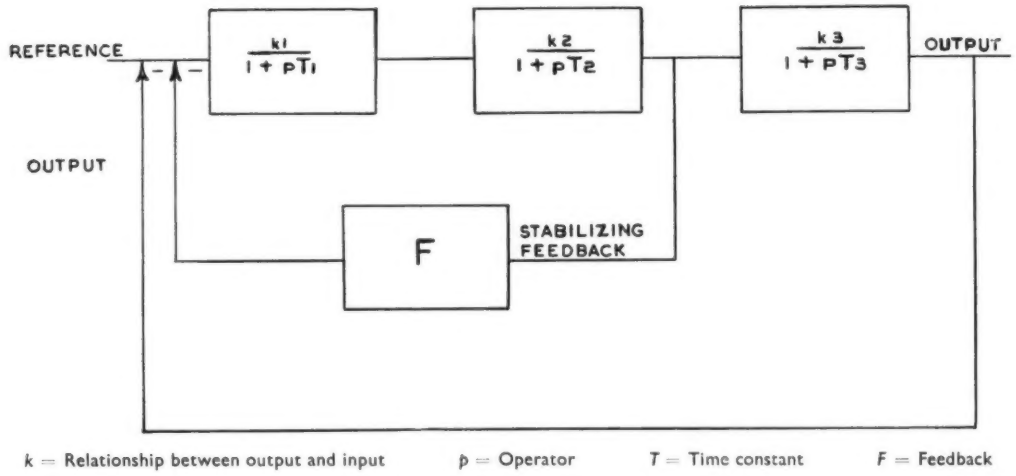


Fig. 4.—Block diagram of three-stage system

applied to the generator field, the output voltage rises exponentially as in Fig. 3(*b*) according to the solution of Equation (1) above, which is,

$$\text{Output} = \frac{k}{1+k}\left(1 - e - \frac{t\ (1+k)}{T}\right) \times \text{Input}$$

If the time constant T is long, the rise will obviously be much slower than if T is short. However, if k is high the value of T is effectively reduced by a factor of $(1 + k)$, so that the speed of response—which is the time taken to reach the final value of output voltage—is dependent not only on T, but also on k. Thus a high value of k is desirable from the point of view of both the accuracy and the speed of response.

(c) *Stability*

If now several stages of amplification each with its own transfer function are considered, as in Fig. 4, the response of the system may be calculated by the solution of the equation,

$$\text{Output} = \frac{k_1 k_2 k_3}{[k_1 k_2 k_3 + (1 + pT_1)\ (1 + pT_2)\ (1 + pT_3)]} \times \text{Reference}$$

It is feasible that since the output of each successive stage lags its input, the final output could be 180° out of phase with the original signal. Since the final output signal is subtracted from the reference and it is 180° out of phase, then when fed back it will tend to increase the error instead of decreasing it. If the increase in output for a change of error is greater than the original change in error, the system has become self-oscillatory, but if the change in output is less then the original change of error, the system will oscillate down to a steady value.

For most of the systems considered here the solution of the equation above would show that the response was either violently oscillatory or unstable (i.e. the oscillations do not die away, but remain constant or increase). Since it would be a lengthy and tedious process to recalculate the response each time a change is made in an attempt to reduce the oscillations, a simple graphical method is used to determine the amount of oscillation that can be expected.

The term $1 + pT$ may also be written $1 + j\omega T$, which in turn can be represented as $r \angle \theta$, i.e. a vector of magnitude $r = \sqrt{[1 + (\omega T)^2]}$ at an angle $tan^{-1}\ \omega T$. Thus the length of the vector and its angle may be calculated for different values of ω, and plotted accordingly. Since at $\omega = \infty$, θ is 90° it follows that a single time constant stage can give a maximum out-of-phase of 90°.

If then a plot of the vector lengths and angles of the various terms comprising the forward loop is

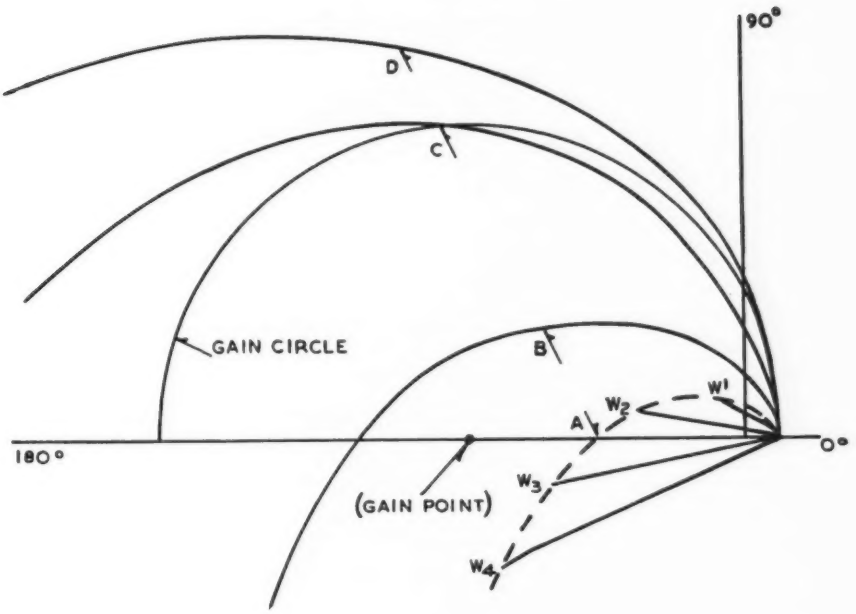


Fig. 5.(a)— 'Q-diagram' of three-time constant system with dissimilar time constants

made for different frequencies, in this case $(1 + pT_1)$ $(1 + pT_2)$ $(1 + pT_3)$, the combined vector would be of the form $r_1\ r_2\ r_3\ \theta_1+\theta_2+\theta_3$ for the different frequencies, and the resulting locus would appear as on Fig. 5(*a*) with the dotted envelope A.

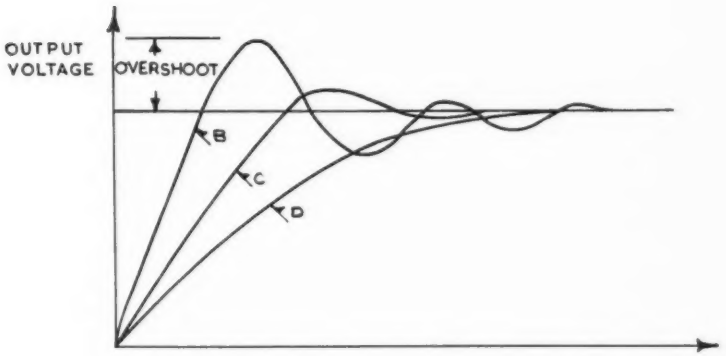


Fig. 5.(b) Response of loci of Fig. 5.(a)

It is here that Nyquist's criterion is used, which in its most practical form means that if at 180° the locus of the vectors cuts the 180° line to the right hand side of the gain point (called −1 point) then the system is unstable. If, as in curves B, C & D, the locus is to the left hand side of the gain point it is stable but may be oscillatory, depending on where it cuts the 180° line and gain circle. The responses of Fig. 5(*b*) are calculated from curves B, C & D of Fig. 5(*a*) and the results can be seen.

Curves B, C & D are obtained from curve A by adding stabilising signals which have the effect at any frequency of pushing the vectors into the stable operating range. This damping or anti-hunt signal would be inserted as shown on block F of Fig. 4. The effect is that transiently the system is stabilised, but the steady state conditions of accuracy are unaffected. Thus the stability is a function of the time constants and the value of the voltage amplification.

At this stage there is one final point that it is necessary to introduce. Occasionally the vectors

do not have the form $1 + pT$, but are merely pT. With this, which is termed an integration, it will be apparent from what has previously been described that the vector always has an angle of 90°, and has the effect of moving the total locus round by up to 90° i.e., the system is de-stabilised by that amount.

From this it can be seen that the accuracy, speed of response and stabilising have to be reconciled in order to achieve correct operation.

Non-Linearities—Analogue Computer

The theory of control system analysis outlined above has contributed greatly to the development of modern industrial processes. In its simple form however it assumes that the system is linear, whereas in practice non-linearities may occur, such as saturation in magnetic circuits, backlash in gear-boxes, and dead zones in the response of electrical devices.

The satisfactory analysis of such systems is difficult mathematically, and to aid him the control system designer has today an invaluable tool in the analogue computer. In this type of computer electronic circuits can be adjusted to simulate accurately the various transfer functions in a loop, including non-linearities. The computer gives a trace that shows how the practical system will perform. The simulating circuits or analogues are electronic amplifiers which may be interconnected and modified by networks to correspond to the performance equations of the system under consideration. External signals provide inputs which apply either the normal or disturbance conditions expected, and the results can be recorded either permanently by pen-recorder, or transiently by cathode ray oscilloscope. These results can then be translated into the effect of various operational conditions on the full scale system.

In addition to saving considerable design engineering time and enabling alternative systems to be investigated, the computer avoids many of the approximations inevitable in a mathematical analysis, where there are non-linearities. The net result is a more accurate prediction of site performance, enabling the best system to be chosen. In a recent analysis the overshoot increased from 5% to 25% when account was taken of gear box backlash. Although this was not critical, the previous knowledge enabled the scheme to be so set up beforehand that very little adjustment was necessary on site. Such prior knowledge of problems to be expected is essential for smooth and speedy installation.

As control systems increase in complexity to meet more stringent performance requirements, and to take over more of the human operator's control function, the design problems become more difficult. Analogue computers are, therefore, an essential tool in further development.

POWER SOURCES AND COMPONENTS

In a review of control system development it is desirable to highlight briefly the main points in the development and application of power sources and components, and a digression to do this is appropriate at this stage.

Power sources

Consider the power sources first. Four main forms of electric power are used :—

(1) 50 c/s a.c. main supply. This is transformed and distributed at two or three different voltages and used mainly for constant speed drives or drives requiring relatively simple control.

(2) Constant voltage works d.c. supply, used mainly for contactor controlled d.c. motors.

(3) Variable voltage d.c., used mainly for the type of drive and process being considered in this paper, where rapid and accurate control is required or regenerative features are required for economic running.

(4) Variable frequency a.c. and low frequency a.c., used at the moment mainly for drives involving a number of small a.c. motors.

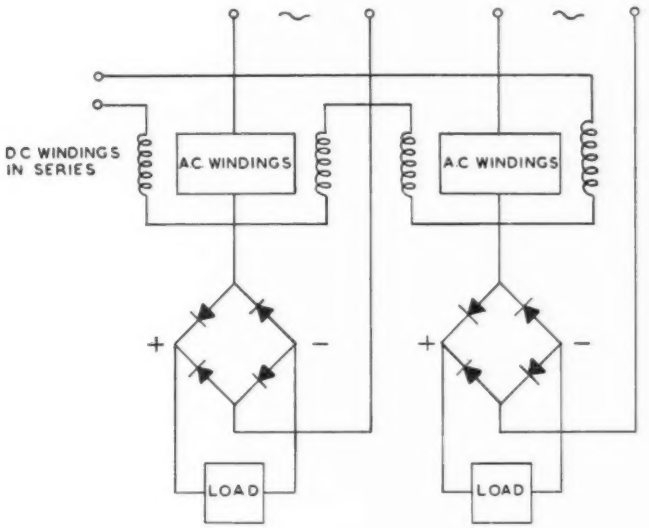
The third of these power sources is the most important in relation to this paper. To provide it, two main forms of converter are at present widely used : the motor-generator set and the mercury arc converter.

The motor-generator set has served this purpose from the beginning and is still widely used. It has

four advantages. It requires comparatively simple control systems ; it uses an a.c. motor which does not introduce significant harmonics into the supply system ; it can be a synchronous machine to help the power factor ; it can be provided with a flywheel, to absorb the peaks of an intermittent drive and ease the duty on the supply system.

Nevertheless, these are outweighed by the advantages possessed by the mercury arc converter that has in recent years been replacing the M.G. set in many variable voltage systems. The mercury arc converter efficiency is normally better ; it is static and easier to maintain ; it requires less foundations and is more flexible to layout ; and it permits extremely rapid control.

Even after satisfactory units became available the adoption of the mercury arc converter was gradual, because certain characteristics can be a disadvantage in some circumstances. Firstly, the power supply must have sufficient capacity to withstand the power peaks without excessive voltage fluctuations. Secondly, due to the one-way conducting feature their control systems are inevitably more complicated. Thirdly, they can introduce harmonics into the supply system. Lastly, they provide a poor power factor load



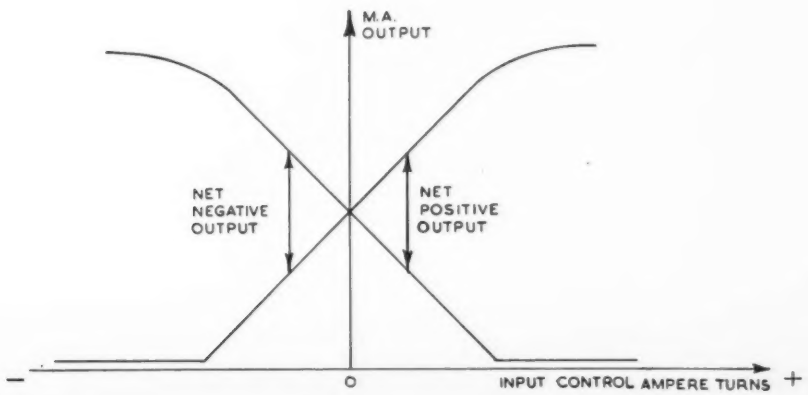


Fig. 6.—Output characteristic of push-pull magnetic amplifier, and basic schematic diagram

M.A. = Magnetic amplifier

when operating at a low voltage by grid control. However, these disadvantages can now be accepted in the majority of cases, with the result that converters are being adopted to an increasing extent.

A variable frequency, variable voltage supply can give an a.c. squirrel cage motor the same main characteristics as a Ward-Leonard d.c. drive. A system of control using this type of power source is therefore attractive in view of the simpler construction of the squirrel cage motor, particularly where several motors are controlled. However, the use of variable voltage variable frequency a.c. systems is limited, because of the difficulty of producing the supply and giving the control that can be obtained with variable voltage d.c.—particularly in large power outputs. At present its use in steelworks is mainly for individual roller drives of low horsepowers.

Components

The increasing use of the mercury arc converter as a power source in place of the M.G. set is one aspect of a marked trend in recent development towards static devices, with their easier maintenance. This same trend is also seen clearly in the components that make up a control system. High reliability with minimum maintenance is of continually increasing importance in components, in view of the rapidly increasing numbers used in modern systems. Static devices aid this. The magnetic amplifier has been steadily replacing the electronic amplifier and rotating exciter. The static switching device is rivalling the contactor in certain fields. The photocell and magnetic proximity limit switch are replacing the mechanically operated contact limit switch. The magnetic amplifiers in the control systems considered in this paper have in fact had world-wide application.

The magnetic amplifier is frequently employed as the primary amplifier to provide the intelligence for the control fields of the machine or exciter stage, and is fundamentally the same in construction as a transformer. Using single, or three-phase supply voltages, 50 or 400 c/s (or higher) supply frequencies and a.c., or uni-, or bi-directional d.c. outputs, it controls the power to a load by saturation of a magnetic core. Controlling the saturation by a d.c. signal varies the output in a linear manner.

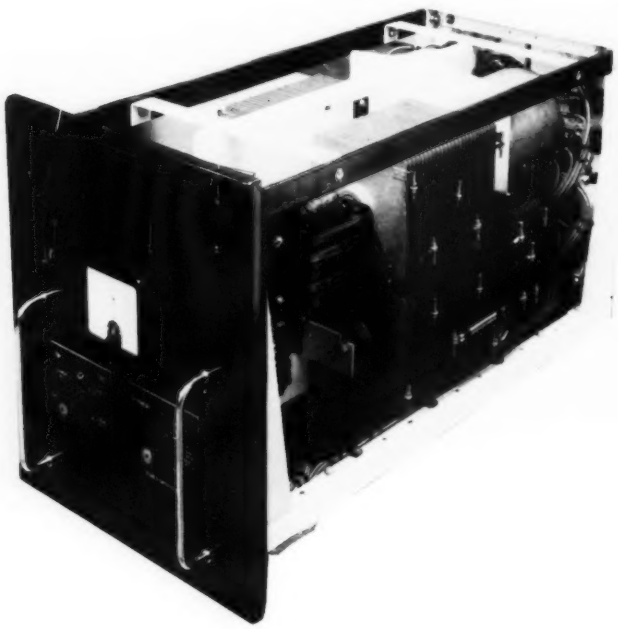


Fig. 7.—Magnetic amplifier chassis

The output is uni-directional (or single ended), but since many control systems require an output which will respond positively or negatively to a corresponding positive or negative input swing, two units are connected back-to-back to give push-pull output, shown in Fig. 6 together with the output characteristic also shown here. Each amplifier has several windings on which to mix the signals and provide isolated circuits. The advantage of the higher frequency is that the time delay is reduced for a given amplification and the size (governed by the iron area) is similarly reduced. The advantages of no maintenance, hermetic sealing, insensitivity to temperature change, low

input power requirements, their resistance to shock and vibration, the flexibility, accuracy and easy installation all tend to make it a most useful device. Monitoring facilities can be included, as shown in Fig. 7.

Another component is the transistor, a semi-conductor device that has been adopted as a multi-purpose component either as a switch, amplifier or output unit. Although used initially for increased reliability there are additional advantages over existing electronic and magnetic amplifier equipments. Their drift is lower than electronic amplifiers and their small size lends itself to their use in programmed and storage circuits, and particularly computer circuits where miniaturisation is essential. The stage however has not been reached where they will replace normal industrial relays either in cost or simplicity.

The normal trend to be expected is towards devices which are more compact, less expensive and still more reliable. Some years ago, because of their reliability, magnetic amplifiers replaced valve amplifiers where it was possible. Now the transistor amplifier is providing the same characteristics as the valve amplifier with much greater reliability. Semi-conductor rectifier devices are replacing the mercury arc converters for certain applications, and controlled static rectifying devices are likely to replace the magnetic amplifier and the mercury arc converter, at least in the lower power ratings, during the next few years.

One further trend is inevitable. The complex circuits and the large number of components involved in the more complex control circuits likely to be developed over the next few years would make the maintenance man's task impossible if all these components were mounted as separate units. Therefore, the circuits and components will be divided into sections and these sections

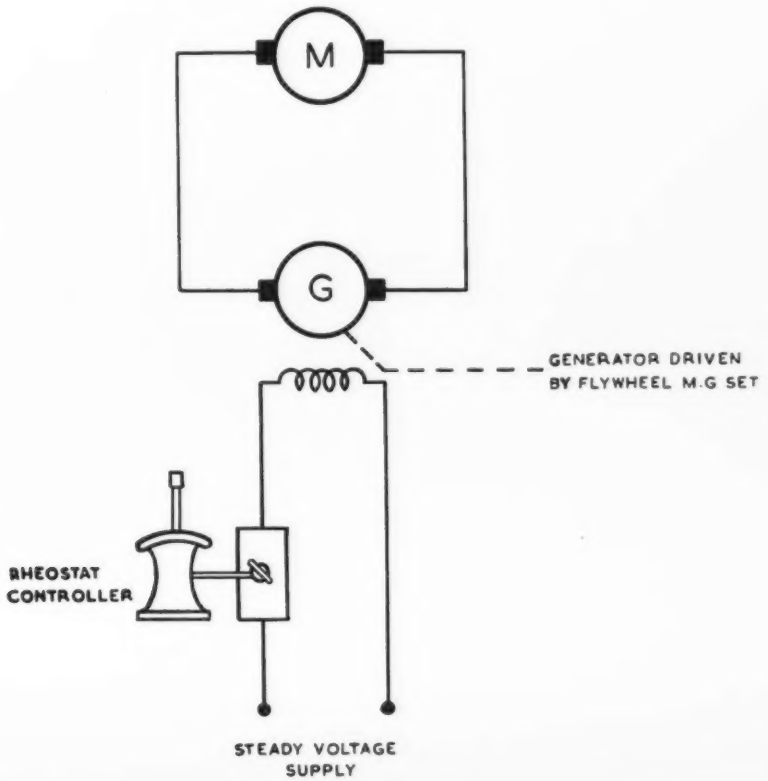


Fig. 8.—Voltage control scheme of 1909

M.G. = Motor generator
M = Motor set
G = Generator

mounted in unit chassis which can be removed *en bloc* and replaced with a standby unit. The magnetic amplifier construction shown in Fig. 7 illustrates this point.

TYPES OF CONTROL SYSTEM

Heavy industry uses a wide variety of control systems, but the ones that are being considered and those that will form an intrinsic part of future development are the closed loop systems for controlling voltage, current, power, speed, and position.

Consideration of the problems involved in these five systems shows how the factors already described affect the design and choice of circuits.

It should be emphasised at this stage that since these types of scheme are in wide use, purely descriptive matter has been avoided as far as possible. The aim has been to bring out the features and limiting conditions which determine the reasons for their use.

Voltage Control

The control to hold the voltage of a.c. and d.c. generators constant was one of the first industrial examples of this type of system. They were however regulating systems of a limited range and rate of response, and not suitable for continuous control over the whole voltage range. Voltage control is the commonest example of feedback control and it is also the fundamental method, in that other quantities such as speed and current are usually controlled indirectly via a voltage measuring device. Furthermore, a system controlling, say, position, often includes a self-contained voltage control loop within the main loop.

The most widely used system is that of d.c. voltage control, and the examples are predominantly based on this. The main application is in drives requiring rapid or accurate control, and one example will illustrate the main points : the reversing primary mill.

Fig. 8 shows the basic diagram for the control scheme being considered in the discussion referred to in the Introduction. Fig. 9 shows the basic diagram for a mill being commissioned this year in South Africa. The later system is obviously more complex and involves more equipment, but the advantages thereby gained, and which are universally accepted, are many. The differences of particular interest are :—

(*a*) The control on the new mill is a closed loop system which rapidly varies the voltage to the value requested by the operator and holds it at that value independent of external factors. The operator is therefore relieved of having to compensate for such things as voltage drop due to load, and variation due to temperature. Therefore, whilst he still gives the command as to what is required he is moved further back in the control chain, in that once the command has been given the system maintains the conditions of voltage required.

(*b*) The use of a closed loop with high gain amplifiers enables considerably more forcing to be applied economically to give rapid response and enables the system to be so designed as to give a linear change in voltage. Thus the more rapid response does not necessarily subject the equipment to more arduous conditions.

(*c*) The high gains also allow small controlling forces to be used. This enables the operator control line to be reduced in size ; in fact, its size is limited now by purely physical, not electrical, considerations. More important, the small controlling forces required enable all the feedback signals, such as current limit, to be economically used.

(*d*) All the machines on the modern drive—the exciters and the main generators and motors—have laminated field frames. These are employed in the case of the exciters in order to improve the rate of response required in the control system. While less necessary for this reason in the case of the main machines, they are of great advantage in aiding commutation under transient load changes and this enables the maximum advantage to be taken of the rapid control available.

In the generator voltage control a one kilowatt single-phase 400 c/s magnetic amplifier (GMA) which acts as an error detector and signal mixing

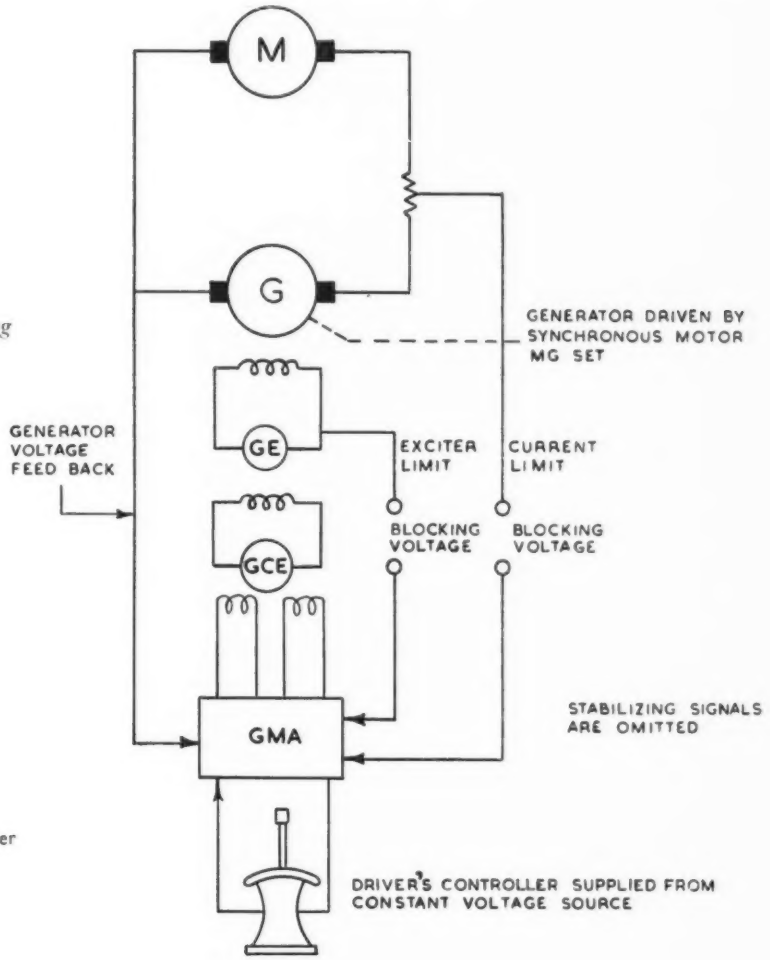


Fig. 9.—Modern hot reversing mill voltage control

G.M.A. = Generator magnetic amplifier
G.C.E. = Generator control exciter
G.E. = Generator exciter
G = Generator
M = Motor

unit feeds a separately excited d.c. machine (GCE). This in turn controls the main exciter (GE) supplying the generator field. A reference signal (from a constant voltage source) is provided via the master controller initiated by the mill operator.

The number of amplification stages has been determined by both economic and technical considerations though sometimes the small magnetic amplifier and the exciter are replaced by a single large magnetic amplifier. Equally, two magnetic amplifiers could be used without an exciter or a magnetic amplifier and a mercury arc rectifier used to feed the main generator fields. Any of these systems can be designed to give a good performance.

The block diagram for this scheme is as shown in Fig. 10. The main forward loop comprising the amplifiers and generator are in blocks 1 to 4. A typical design would be to give voltage reversal from fully positive to fully negative in three-quarters of a second, the accuracy at this voltage being at least a quarter of one per cent, since enough amplification has to built into the scheme to give the speed of response. Thus in this case the accuracy has not been the limiting feature. The number of time constants and the amplification

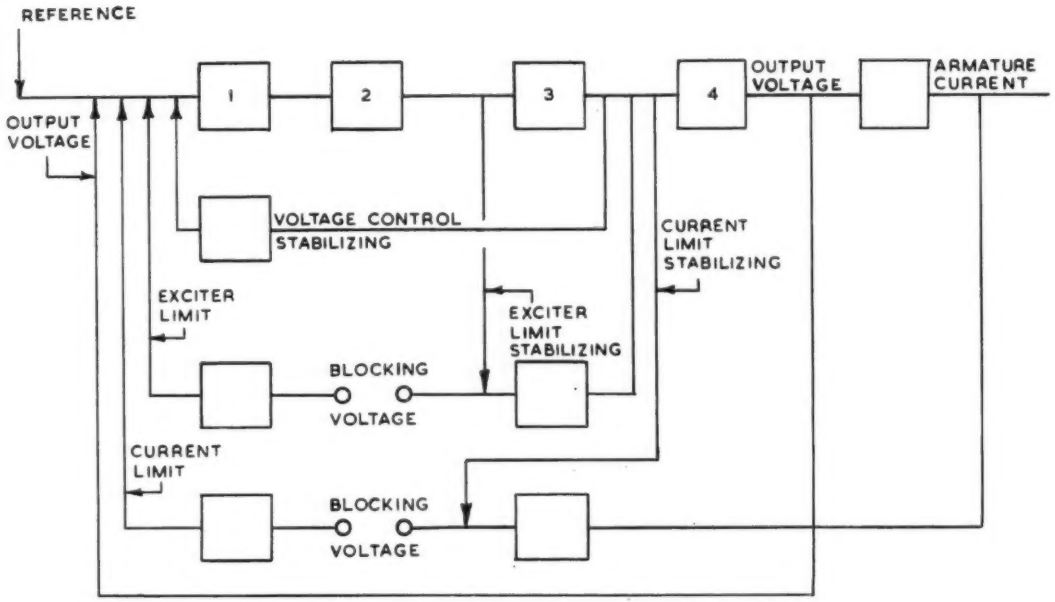


Fig. 10.—Block diagram of hot reversing mill voltage control

necessitate the use of stabilising signals, and these are shown.

However, in addition to the basic variable voltage control there are several other features. Firstly, there is a current limit which protects the main machines from the rapid current changes inherent in a fast response scheme. This requires a separate analysis which would show that stabilising feedbacks are also required for this current limit. Furthermore, it often transpires that to protect the mechanical parts of a drive during the initial stages of a new installation the high designed performance is not required, hence some means of adjusting it is needed. This introduces the second feature, i.e., the exciter voltage limit which by limiting the peak output of the exciter slows down the generator voltage response. Again a stabilising signal is required, owing to the naturally oscillatory nature of this control when it is operating.

It can be seen therefore how the complete block diagram of the variable voltage control is constructed. It may appear complicated, but this is necessary to do the job : it cannot be done more simply.

The various components used however do not always behave in the ideal manner assumed for calculation purposes, and although the design techniques and computers available to the system designer enable the performance to be closely predicted, there are a number of practical features which have to be taken care of, e.g. generator exciter residual voltage, the effect of which can be seen by considering the following.

Fig. 11 shows how the voltage in the various stages behaves during a change and it will be noted that in this case the voltage applied to the generator field by the generator exciter (GE) reaches a peak of approximately ten times normal. Values much higher than this may be used in exceptional cases, although eight to ten times is reasonable. As this machine carries out the main forcing function it must also give full output voltage on the generator under the steady state conditions, i.e. for about fifty volts. Thus if the residual voltage is 2%, then for a peak output of 500 volts the residual is 10 volts or 20% of normal output. Although this is reduced by the control, it may cause creep on a main drive and heavy circulating currents on drives

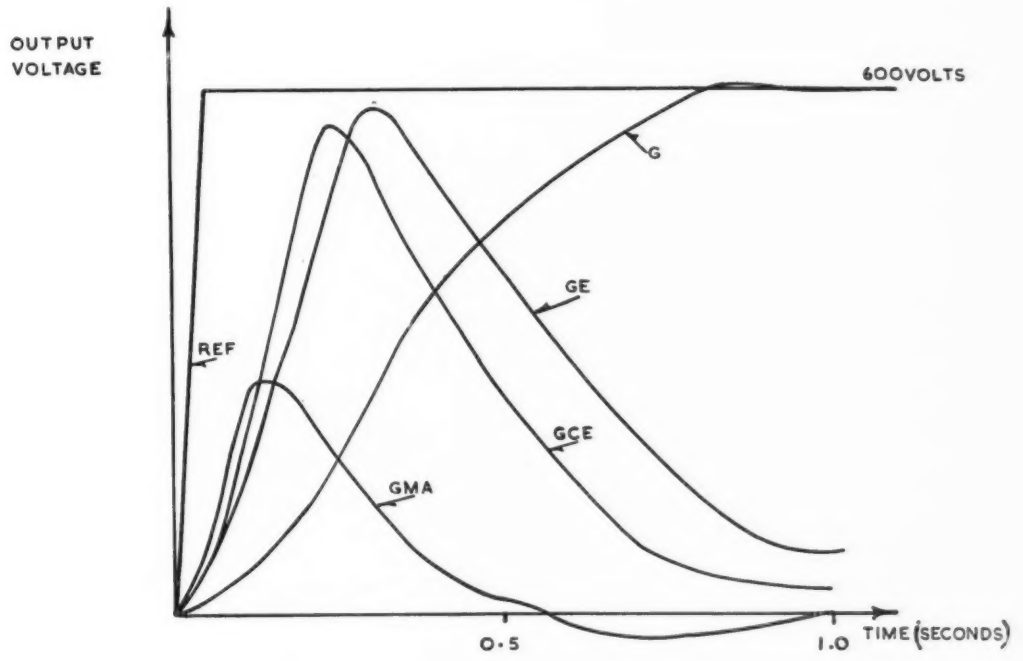
fitted with brakes. On the latter, therefore, it is important to provide stall protection against a high circulating current at low generator voltages.

Again temperature effects raise and lower the exciter operating voltages (owing to changes in the resistance of the main generator fields).

However, a properly designed control only alters if its reference or its output changes. Hence the servo would take account of these temperature changes within the loop, provided reasonable precautions are taken with the input and output components (usually resistances) to ensure that they are not temperature sensitive.

Where eddy currents are involved another factor may be added to the block diagram, as it is normally assumed that a machine output voltage is in phase with its field current. On non-laminated frames of course this is not so, and the effect is approximately to add another time constant into the forward loop, thus de-stabilising it. Hence a wide variety of problems have to be considered.

This Ward-Leonard system is of course a transformation of electrical energy to mechanical energy and then back again. The last transformation gives a very good d.c. voltage which is easily controlled, and for this reason has wide application throughout industry. However, it is far more efficient if the transformation can be done without going through a mechanical stage, i.e. without the Ilgner set or M.G. set, and where d.c. is still required this can be done by using a converter. Any consideration of control schemes therefore would be incomplete without a study of the way in which converter devices can be controlled to give the characteristics required. The brief example following illustrates the different type of approach



G.M.A. = Generator magnetic amplifier G.C.E. = Generator control exciter G.E. = Generator exciter
G = Generator REF = Reference

Fig. 11.—Actual voltages for off-to-base speed step

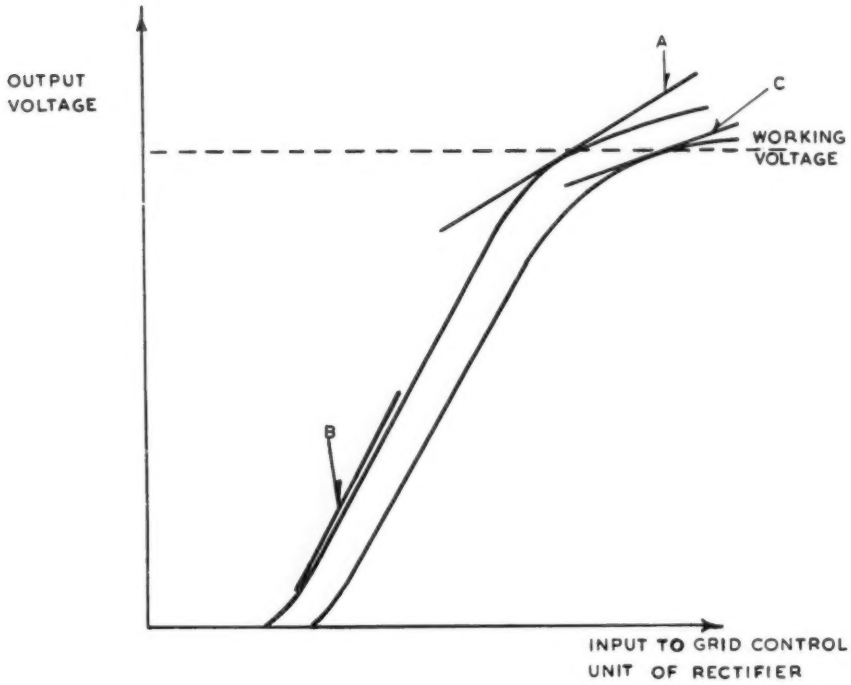


Fig. 12.— Rectifier characteristic showing change of operating gain

required from the generator control where the emphasis is on obtaining a fast response.

Since there are no large time constants with a converter there is no problem of 'forcing' the control and the criterion is that of accuracy.

The principal factors which affect this converter voltage control are :

(1) the maintaining of the d.c. output voltage constant at a set value to an accuracy of less than 0·25% when influenced by such external changes as loads suddenly applied, a.c. supply fluctuations, and temperature changes in the equipment.
(2) a quick response and hence a short recovery time to any change.
(3) adjustability over whole or part of the voltage range.

The basic feedback control scheme operates in a similar manner to the generator voltage control with a magnetic amplifier feeding the grid circuits of the converter directly. However, in this case the control is required to operate over the wide range of the converter characteristics shown in Fig. 12. The system must therefore be designed for this range of gain and still meet the performance specification. Three cases are considered :—

Normal working slope (line A)

Low output for inching (line B)

Normal working at 150% full load and 95% a.c. supply voltage (line C)

The most suitable design arranges that under the high gain condition, fixed by the slope of the tangent to the curve B, there will be slightly more overshoot and the low gain condition C will be more damped than for normal working conditions. Furthermore, with a converter control any signal from the main loop must be adequately filtered and effective smoothing employed, otherwise the ripple may render the servo partially inoperative. Since these filters (inductance, resistance, and capacitance) themselves have time constants, they must be considered in the analysis.

Current Control

Rather than merely extend the voltage control analysis, an example is taken of an entirely different type of current control which, because the input voltage remains to all intents and purposes constant, is really a power control.

This example, which is familiar to everyone, is the control of the slip-ring induction motor driving an Ilgner set. The system adopted is to measure the a.c. current (by a device giving a voltage ouput proportional to current, i.e. a current transformer) and when it reaches a pre-determined level to keep it at this value by a control system which increases the resistance in the rotor circuit.

This system, however, has two snags. Firstly, the gain is low and any stiction or irregularities in the performance of the liquid controller can cause errors in operation. Secondly, the system is inherently unstable owing to the double integration (caused by the controller movement and the torque motor characteristic) in the circuit. Damping has to be employed to correct this, thus slowing down the effectiveness of the control. It is undesirable to have a wide margin of operation on a regulator of this type, since this increases the allowable maximum peak from the supply. For this reason either hydraulic (frequently on mine winder controllers) or Ward-Leonard control with a high gain is now employed in many cases. The important change is the elimination of the torque motor and the introduction of a small Ward-Leonard system which allows more flexibility and adjustment in the design. This elimination of the unknown or changeable factors occurs continually in control system development.

Power Control for Strip Heating

Electrolytic tinplate has a matt finish which is flow melted before it can be used commercially. This is done by heating the tinplate strip to the melting point of tin by passing heavy a.c. currents through the strip, which is enclosed in a muffle.

This example differs from the previous one in that the power that is being controlled is via an a.c. voltage control. In order, however, to design the control satisfactorily the a.c. voltage is rectified

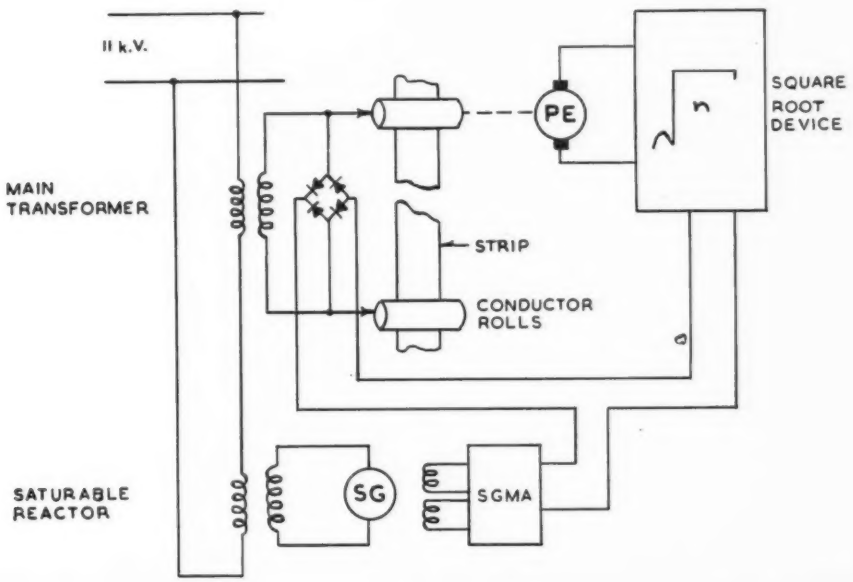


Fig. 13.— Re-flow line basic schematic diagram

P.E. = Pilot exciter
S.G. = Saturating generator
S.G.M.A. = Saturating generator magnetic amplifier
n = Strip speed

by a full wave bridge and smoothed, so that in effect the mean output voltage is the true controlled quantity.

Fig. 13 shows the simplified arrangement of control. The primary voltage of the transformer is 11 kV, which is transformed down to 210 volts. In series with the primary of the transformer is a saturable reactor, and by varying the d.c. current flowing in a saturating winding the impedance of this reactor can be varied over a wide range, thereby varying the voltage applied to the transformer primary. The transformer secondary winding is connected to conductor rolls in contact with the strip so that the current flows along the strip between these rolls.

The power to heat the strip is proportional to the square of the voltage across the strip, and it can also be proved that the power is proportional to the strip speed for a given cross sectional area so that

$$\text{Voltage} \propto \sqrt{(\text{Strip speed})}$$

Hence by maintaining the voltage across the strip proportional to the square root of the strip speed, an a.c. power control is obtained. If there is a reference proportional to the square root of the strip speed measured by d.c. pilot exciter PE, the voltage output will be controlled to follow this characteristic. Any difference between the feedback voltage obtained from the rectified transformer secondary winding and this square root reference is applied to the control winding of the magnetic amplifier SGMA, so that the saturating generator SG output and the transformer secondary output are all altered to bring the last quantity to a value corresponding with the square root of the actual speed at that instant.

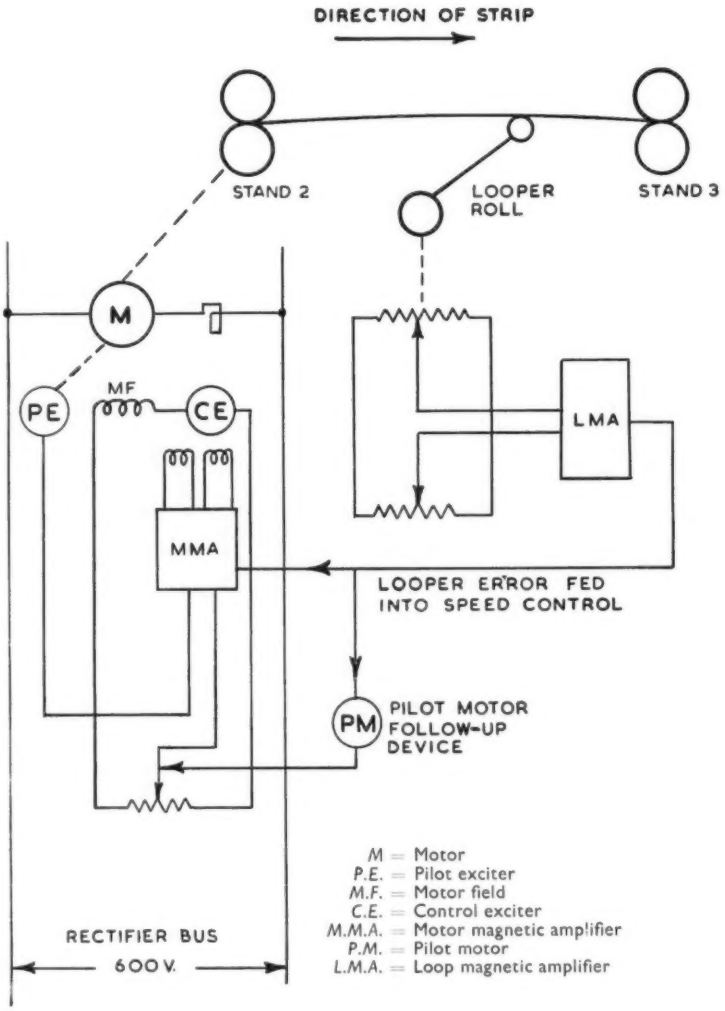


Fig. 14.—Speed control for hot continuous mill, showing looper control

This is rather an unusual example of the application of closed loop control to provide control at high strip speeds which it is not possible for an operator to provide satisfactorily. It is an example of not merely helping the operator to achieve the performance and reduce his fatigue, but of enabling

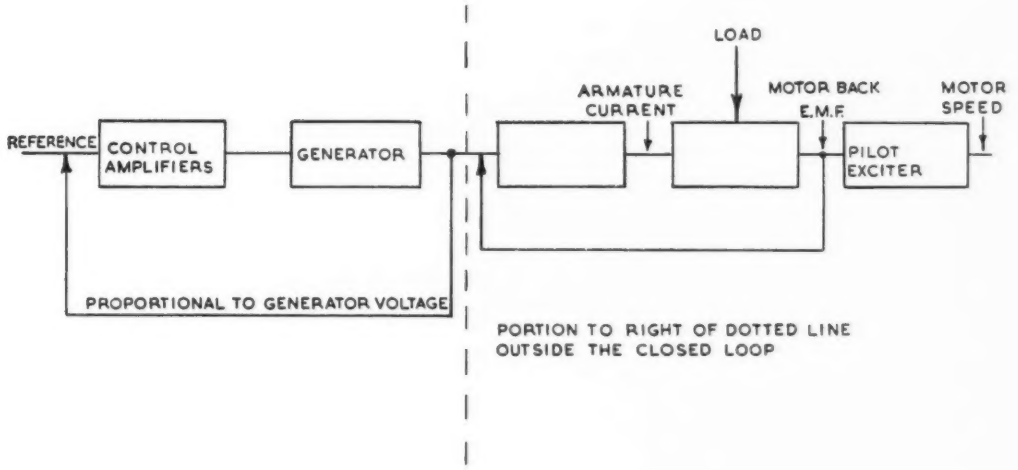


FIGURE 15 (a)

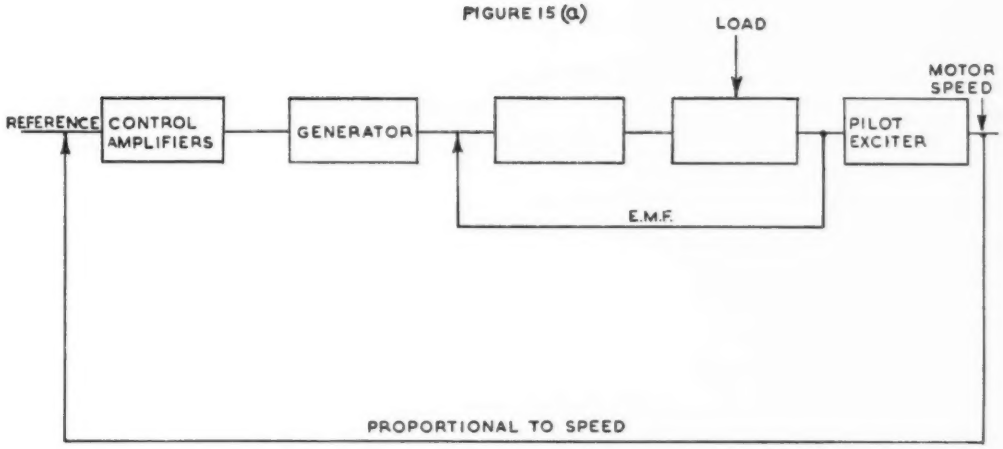


FIGURE 15 (b)

Fig. 15.—*Block diagrams of voltage and speed controls*

something to be done which a human operator is not capable of doing.

Speed Control

Although voltage control meets the speed control requirements of many drives, many variables are left uncontrolled whose influence results in the unsatisfactory performance of some systems. The main effects are speed variations that can occur with load and with changes in armature and field temperature.

One example of this in a steel works is the hot continuous mill. Here the piece is entering a number of stands in succession at speed and the variations that take place as the nose of the piece enters each stand can cause stretching and looping.

These are in general undesirable, and in the higher speed mills unacceptable.

The slower speed changes due to the armature reaction effect and the temperature effect can be and are on many mills compensated for when necessary by the operator. However, the transient load effect that occurs on entry is too rapid for any operator to do anything about. For this reason modern hot continuous mills use a speed holding control basically as shown in Fig. 14.

It is interesting to note here two points in relation to our opening theme. Firstly, the transient load effects occur so rapidly that the operator cannot do anything about them. Therefore, if they become unacceptable as the speeds of mills increase, a control scheme must be installed to reduce these effects to a minimum. Secondly, the other variations that occur can be compensated for by the operator if he is watching the mill continuously, but in fact a speed control which overcomes the transient speed difficulties automatically compensates for these longer term effects. The operator again has been set one step further back in the chain of control, in that now he sets the actual value of the speed he requires and the control system holds this speed for all conditions.

Fig. 15(*a*) and 15(*b*) show the block diagrams of an armature voltage control system for a motor and for a speed control system, acting through armature voltage. The use of speed control introduces two additional time constants into the control loop—the electrical time constant of the armature circuit and the mechanical time constant of the armature and load being driven. In the light of what has already been said it is obvious that the speed control system presents additional problems to the control system designer. This clearly demonstrates that the more variables it is attempted to control in taking over functions of the human operator, the more problems have to be solved in the design of a system and the more complicated is the equipment.

In some instances, however, the additional complication may be relatively small. An extension of the speed control system in hot strip mills illustrates this. A straightforward speed control system simply holds the drive at the speed set by the operator. If the speeds of the various stands are incorrect, trouble will still be experienced in rolling due to looping or stretching between stands. In many mills therefore it is useful to provide a control system which will automatically correct for any error in the speed of the stands. This can be done by taking a signal from the loopers between stands and feeding the signal into the speed control system of the following motor, to speed it up when the loop is too high or slow it down when the loop is too tight. Alternatively, of course, the speed of the preceding motor can be varied in the opposite manner. This additional feature can be added into the motor control system without much difficulty.

The basic speed control system shown in Fig. 15(*b*) introduces a factor which is of considerable importance in many systems—the use of a sensing device to provide the feedback signal. In the case of the voltage control system it was easy to obtain a feedback signal since this is normally being generated by a source of ample power output. In most other closed loop systems, however, the satisfactory provision of a feedback system requires careful design. For the speed control it is necessary to provide some form of generator or converter to change the mechanical rotation of the shaft to an electrical signal which is an accurate measure of the speed of rotation under all conditions. The speed sensing device can take a number of forms, although in practice it is usual to use a d.c. tachogenerator. Whatever device is used there are a number of important characteristics that it must have. It must have negligible backlash and temperature effects, occupy the minimum of space, be reliable, and have low power consumption, low regulation and negligible hysteresis. The performance of feedback control systems using transducers is entirely dependent on the truth of the transducer.

Position Control

The job of many drive systems is to carry out a specific movement of a piece of equipment. An obvious example is the screwdown drive on a mill. At present the majority of such drives have a simple voltage control system, either armature contactor and resistor type or variable voltage closed loop. The operator controls the speed of

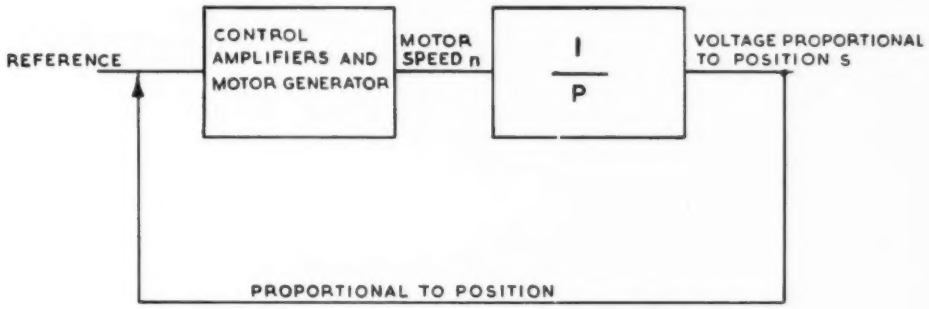
the drive by this system and it is left to him to locate the correct position of the device.

An obvious development is to move the operator further along the chain by providing a system that will accept a command concerning the position required and carry out that command without further action by the operator. In simple systems, with a few positions and not requiring high accuracy and response, this has been done for many years, using limit switches.

Where high rates of response together with high accuracy are required the problems are more difficult. The screwdown for a reversing primary mill is an excellent example. The main requirements of a position control for such a screwdown are that it shall be at least as fast and as accurate in positioning the drive as a human operator ; unless it gets this far it is no use. In order to meet these requirements, several problems have to be overcome. While it is possible with modern amplifiers to obtain sufficient system sensitivity to meet requirements of both accuracy and speed of response, it has been necessary to develop special position measuring devices of sufficient resolution and robustness for steel mill duty. When considering the requirements of such a position measuring device it is necessary to consider three main factors : mechanical robustness ; mechanical backlash in the system ; and a resolution of measurements to meet requirements both of accuracy and of response.

The position control system indicates still further how additional problems are introduced as the operator is moved further up the chain of control. For example, when stopping, the human operator has very good anticipation as to when to move his controller so that the rolls come to rest in the required position. The control system must also have good anticipation, otherwise the position will be overshot or undershot and the time taken to reach the final position will be too long. Similarly the operator becomes very able at overcoming the effects of stiction. The controller is jogged to get the movement that is required. Here again the control must compare in performance, and in fact it can be arranged that in the presence of stiction a higher system gain becomes in effect available to give rise to a high current to overcome the stiction forces. When the drive is moved the gain is reduced to that required to give satisfactory linear performance.

In addition to these problems there is the fact that the position control system fundamentally is more difficult to design. Fig. 16 shows the block diagram and it will be seen that there is the integrating factor of the movement of the position



DISTANCE TRAVELLED = AREA UNDER SPEED / TIME CURVE

SO THAT POSITION $S = \int_0^t n\,dt$ OR $\frac{n}{P}$

p = Operator n = Motor speed

Fig. 16.—Block diagram of position control

measuring device. As shown earlier in discussing fundamentals, this makes additional steps necessary to get stable performance with fast response and high gain to give accuracy. With the use of modern tools and techniques however this can be done readily and system performance predicted very closely. In the last two or three years several position control systems have become available which meet all requirements and which can readily be designed to meet specific requirements. In rate of response and accuracy these systems will always beat the operator, using voltage control.

Where it is necessary to select within a large range of positions however a new problem arises. The operator must have a means of giving a large number of different commands, as against the few commands he needs to give a speed or voltage control system. If he issues separate instructions for each movement as to the actual positions required it means that he has to position a device to give the instruction. Where high accuracy is not required a few installations operating on this principle have proved satisfactory. Their use has not been great because the improved response provided by modern variable voltage control systems has greatly eased the job of the operator where rapid operation is required.

The majority of position control systems involving a wide variety of settings have been on mill screws. These have used a memory system to enable the operator to store the details of his requirements, and so simplify the giving of his command by referring the control system to the memory. Several forms of memory system were used in the earlier equipments using plug boards, limit switches and rheostats and some very good systems were installed and have given satisfactory operation for many years. Their field of adoption however was limited by the storage capacity of the memory system. Memory systems are now available which can store a considerable amount of information, and these will be referred to later.

Simultaneously with the closed loop and memory system development, improved means of giving instructions have been developed. These enable the operator simply and rapidly to feed into the system either the absolute position he wishes to move to or the distance he wants to move in the next action.

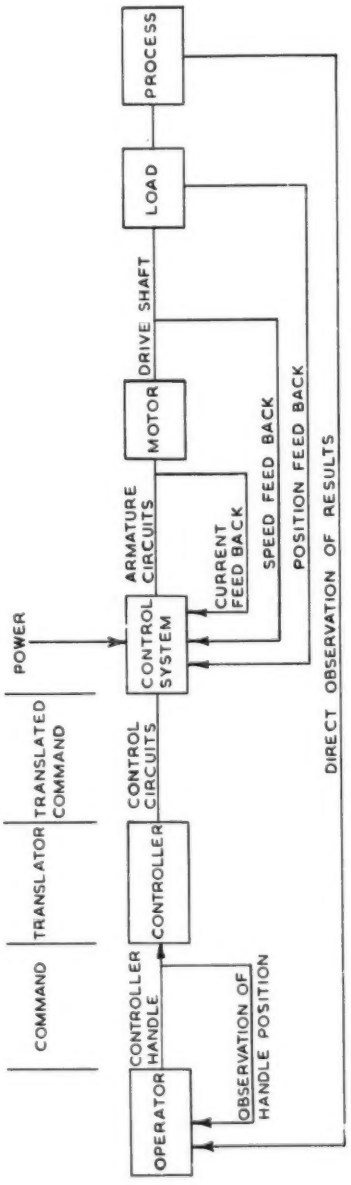


Fig. 17.—Chain of command and control for position feedback control system

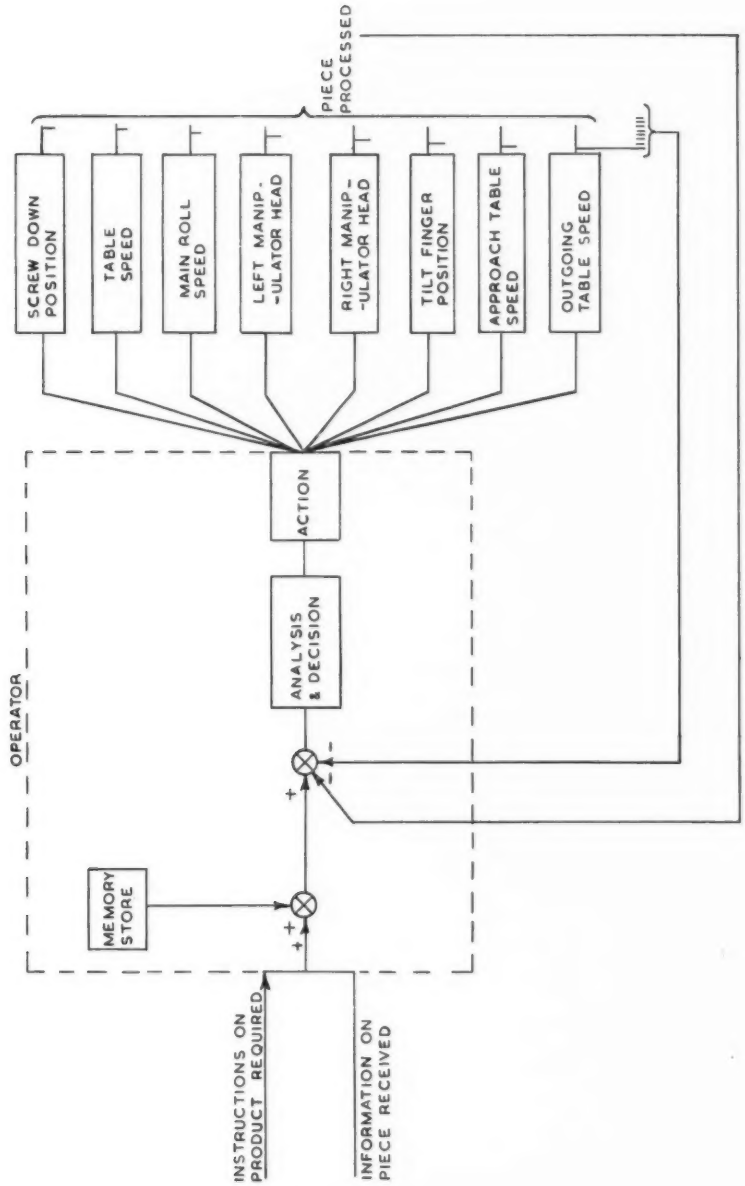


Fig. 18.—Chain of command and control for primary reversing mill

*At the Ackworth Shaft of Ackton Hall Colliery, in the North Eastern Division of the Nation*ard, *installation. Previously the driver's position was in the main body of the winder house,* ving *accurate positioning at landings. Now the driver is housed in an enclosed cabin having* desk *conveyance, making reference to the drum unnecessary.*

A twin 60*-in. stroke steam engine that occupied much of the floor area in the winder house* place *above. This machine has a peak output of* 900 *h.p. over a voltage range of* 3100/3300*V.* All in *controlled down to a ' creep ' speed before being brought to rest finally by mechanical* brak

*The winder is used to convey both men and materials, and although a relatively small exam*ber of *twenty-four hours.*

The mechanical parts of this winder were supplied by M. B. Wild & Co. Ltd., Birmingham.

Nationard, the existing steam winding engine was recently replaced by a modern electrical winding use, ing controlled by reference to a circular-dial type indicator, and the marks on the drum for ving sk fitted with a miniature type depth indicator which gives the precise position of the

house placed by a 570 r.p.m. slipring induction motor, seen to the right of the drum in the picture 00V. d in the control scheme is a dynamic braking system, which enables the winder to be l brak

l exam a of its duty is given by the fact that over a thousand men are carried in the cage every

ngham

FUTURE

The development of satisfactory position control systems can be regarded as completing the groundwork of the first era of control system development in the heavy industrial field. That is, the development of systems which control a complex of power fed devices to produce quickly and accurately the correct value of a single parameter, or a single relationship between parameters, in accordance with a single instruction given by the operator—usually the movement of a handle. A comparison of Fig. 1 and Fig. 17 (which shows the chain of command and control for a position control) indicates how the functions of the operator have been taken over by the control system.

These functions are however only the functions of the operator in relation to the control of one parameter. He performs numerous other functions in his job of operating a process and Fig. 18 shows the wider chain of command and control for a reversing primary mill, illustrating this. The next era of control system development, into which we have already entered, will undoubtedly be towards the replacement of these further operator functions : the functions of memory, observation, co-ordination, analysis, recording and reporting.

In devising systems to take over such functions there is obviously tremendous scope for variety and ingenuity in system design. Some first steps have already been taken and these, together with a look at developments in other control system fields, show the pattern for at least the first stages of this new era of development. In this final section of the paper this likely pattern of development is shown as a logical evolution from the work we have already considered and possibilities for the more remote future indicated.

Memory Systems

The example of the position control system shows quite clearly the next logical step in development. It highlights the fact that where a wide variety of commands have to be given to a control system, the operator has still an appreciable task in giving each instruction accurately. Where the movements can be predetermined, this difficulty can be overcome if a suitable memory system can be devised. This must store the information, giving the accurate details of the positions required in such a manner that the operator can readily refer his position control system to the correct piece of information. Thus, when he gives his command to initiate an operation, the position control system works to accord with the stored information. Simple systems which do this using plugs, limit switches and rheostats have been in successful operation for many years but their storage capacity is limited, and hence their field of application is severely restricted.

In the last few years the adoption of the technique of the automatic telephone exchange, business machine and electronic computer has provided a number of storage systems which meet many of the requirements of heavy industries in this respect. These systems are still in their early years and much development can be expected. However, early examples are in operation on mills, and two of these will be mentioned to illustrate this present stage of development.

Firstly, where information of a fairly permanent nature is to be stored, a system using the uniselector type of switch shown in Fig. 19 can provide a memory which is simple and reasonable in cost. Fig. 20 shows such an equipment for a reversing mill, storing information for the positioning of

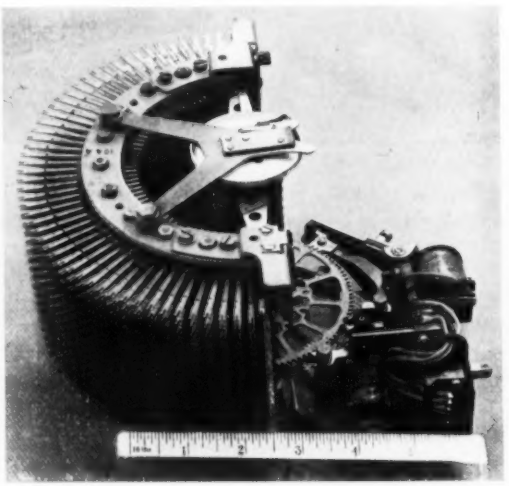


Fig. 19.—A uniselector switch

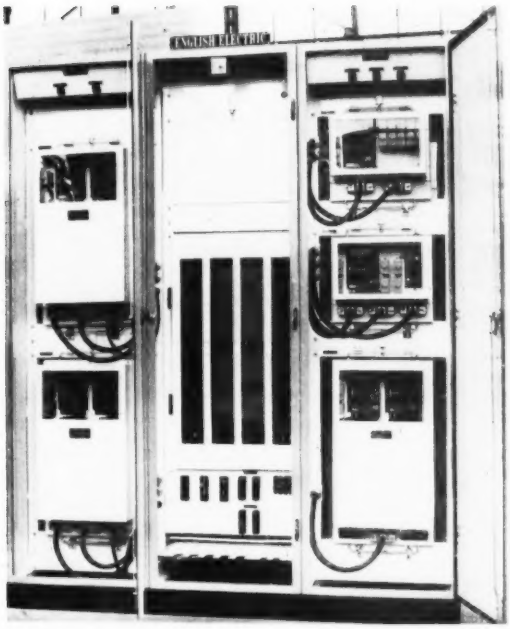


Fig. 20.—Typical equipment for storing information for positioning and setting of a reversing mill

two drives and speed setting of the main drives and tables. The information is wired into the memory system on a matrix of terminals. The operator selects the particular programme required by means of three or four control switches which are positioned according to the ingoing and outgoing dimensions of the piece.

Where a very large variety of information has to be stored, the punched card system used for many years in connection with business machines offers very attractive possibilities. A number of systems using cards has been developed. In these systems the information is stored by punching holes in a card in accordance with a definite scheme. By means of contacts or photocells these cards can be read and information used for operating control systems.

If the standard business card is used, a single card will not store sufficient information to meet the requirements of many mill systems. This can be overcome by adopting the normal procedure in business machine systems of storing the information on a number of cards and reading these cards in rapid succession. In fact a number of systems are in operation using standard business machine readers in just this manner. The information for a programme is stored on the necessary number of cards. These cards are read by a standard card reader and the information fed from this into an intermediate memory system, which stores the information taken from the cards for as long as is required. The individual speed and position control systems are referred to this intermediate memory for information.

The intermediate memory system can be quite a complex transistor network. It can be avoided if the system is designed so that all the information for one sequence is stored on a single card. The individual control systems are then referred to this card for information. In such systems the

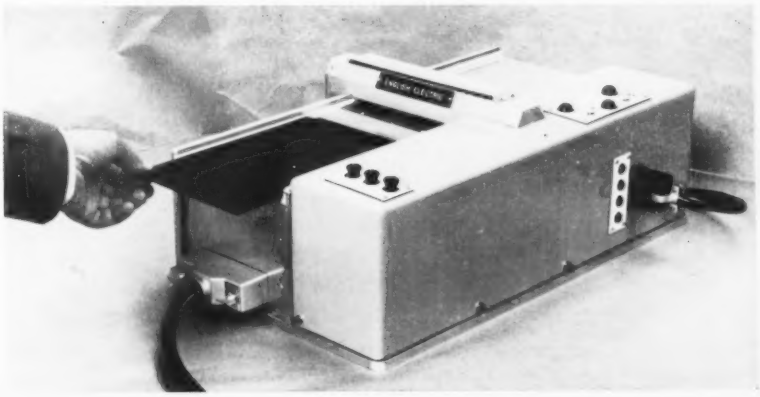


Fig. 21.—A card reader unit

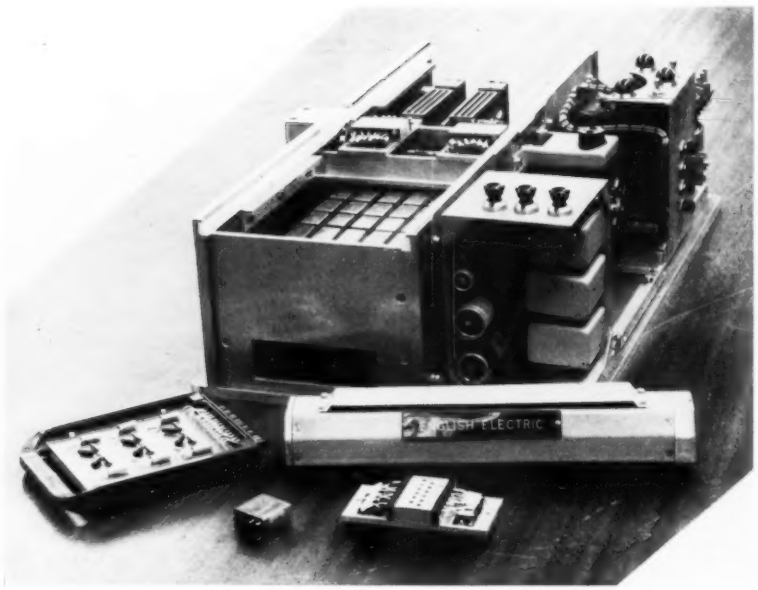


Fig. 22.—The unit in Fig. 21 dismantled. In the foreground are (left to right) a unit containing a group of amplifiers which receive signals from the photocells; one of the relays supplying the outgoing signals; and a base containing a group of photocells. Behind the photocells group is the light unit

card can either remain static and be read by a matrix of photocells or can move so that each line or pair of lines is read in succession by a line of photocells. One of the applications where these systems have first come into use is for the control of reversing mills. In many of these mills it is necessary to use a special large card if all the information required for each programme is to be stored on a single card. Fig. 21 shows a card reader unit of this type in which the card is moved pass by pass beneath two rows of photocells. In this type of card reader the information for more than one programme cannot be stored. On the other hand the fact that a single card stores all the information for each programme makes it much easier to store and select cards. The cards immediately required can therefore be stored near the operator, who can readily select the card for a particular programme.

Fig. 22 shows the same card reader partly stripped. In front of the reader are four of the component parts. To ease maintenance, all these components are built into self-contained plug-in unit assemblies.

The addition of memory systems to the systems described earlier enables the actual process to be carried out in accordance with a predetermined pattern. This leaves the operator to control only the sequencing of each operation. This eases the operator's job and—what is often more important—gives consistent operation frequently resulting in an increase in yield and improvement in quality.

Sequencing

To replace the operator's function in controlling the sequence of events is logically the next stage in development. Again the first steps have already been taken. The ability of a control system to determine the sequence of events means that any process can be made fully automatic and that it comprises a sequence of operations which can be completely predetermined. The operator has only to issue the initiating command and to choose the programme of operation that he requires.

Numerous sequencing systems using limit switches and photocells have, of course, been in operation for many years and have enabled many production processes to operate automatically. Some of these systems are complex but they are

still simple compared to the performance of a human operator.

Sequencing as the term is used here involves two essential requirements. Firstly, observation, and secondly, the comparison of the observation with stored information. In the early systems using limit switches and photocells, this was relatively easy. The observation compared simply the answer to a question ' yes/no ' for the mechanical position of material and the initiation of one or two possible sequences dependent on the answer.

For many processes, however, a simple observation of this nature is not sufficient to give the sequencing necessary for automatic operation. In the automatic reversing mill, for example, a number of factors have to be observed if correct sequencing is to be obtained—such items as the position of the nose and the tail of the piece at various stages to give the right acceleration and deceleration, as well as the stopping and starting of the main drive and tables ; whether the piece successfully enters the mill or whether another attempt must be made ; and whether the piece has been successfully tilted, or another attempt must be made. By using a number of yes/no devices in the form of infra-red detecting cells positioned in strategic places, a large number of the necessary observations can be made. By this means several reversing mills are operating satisfactorily from completely automatic control systems, particularly mills rolling fairly simple products unlikely to depart from the expected pattern of behaviour.

There is, however, scope for considerable development before control systems even approach the observational capabilities of the human operator.

Measurement

The combination of knowledge storage and sequencing results in an automatic system which in effect makes a series of particular observations of a yes/no variety which initiate predetermined sequences. Notice that there is no closed loop, i.e. no overall feedback of the information from the process output. It is still left to the operator to observe the sequence of events and see that the correct product is being produced.

The third stage of development is therefore clear : to check the product being produced to see that the output from the automatic system is correct. The essential requirement for this is to measure the factors determining the quality of product and to interpret the measurement in terms which can be fed into the control system and understood by it.

There has already been tremendous development in this field and particularly in the continuous process industries such as the oil and the chemical industry. There is, however, scope for considerably more development. It is not too much to say that the standards of quality that can be achieved will be dependent on the ability to measure the factors which matter and feed the results into a control system.

An example of an electrical control system carrying out this function in the steel industry is the automatic gauge control on a cold strip mill. Here the thickness of the strip is measured and compared to the required standard. Any discrepancy is fed back into a control system and the screws and/or tension controlled to modify the operation of the mill so as to return the strip to gauge.

Scientific and industrial progress has always been dependent upon satisfactory measurement of quantities and qualities, and the reporting of these measurements in a form that can be understood by the human operator. Much of the possible development of automatic control systems will depend on the future development of measurement and reporting in a form that can be fed into the control system.

Analysis and Calculation

Where a measurement is being made of a single variable such as the thickness of the strip, this can be compared with a single electrical parameter. The error can be used to control a predetermined sequence in such a manner as to reduce that error. However, in many cases there is more than one measurement involved, and instead of a single predetermined sequence there are a number of sequences dependent upon conditions which vary throughout the day.

In such systems the operator must analyse the various observations and measurements, analyse the conditions affecting the sequence that must be

carried out and decide on the action to be taken. He then issues his instruction to the control systems that are made available to him. This function of analysis and calculation is the next function in the chain of command and control that can be taken over from the operator. The requirements vary greatly according to the process, but there are examples which demonstrate this function of analysis and calculation in isolation from the sequence control and the other controls that have been discussed here.

One such example is the hot saw bench in a section mill. The operator at this bench receives a piece of material whose length is unknown because of the inconsistency of the processes preceding the saw bench. He removes the discard from the nose and measures the length of healthy material. He has previously been told the orders on hand and based on this and the length that he has measured he must rapidly decide the optimum length into which to cut the piece. Although with experience the operator can do surprisingly well he must inevitably lose a little yield due to occasionally choosing the wrong combination of lengths to be cut.

A computer can be provided which will store the order book information. On being told the measured length this computer will rapidly give the optimum length into which the piece should be cut to give the optimum yield. An analysis of several of the problems has shown that an increase in yield of between 1% and 3% can be obtained by the use of such a computer. This is a clear example of where the use of a system to replace an analytical function of the operator can very definitely justify itself on economic grounds.

Computers designed specifically for industrial applications of this kind are becoming increasingly available, and they will play an important role in the development of systems for the steel industry.

Closing the Ring

The addition of analysis and calculation to the functions already discussed enables the loop of the automatic control system to be completely closed. Several factors of the products being produced can be measured and fed into a computer. There they can be compared with the standards which have been previously stored. Discrepancies can be fed to a knowledge store and analytical unit which would decide the correct action to take after analysing the discrepancies and any other factors which have been previously stored. This action is fed into other knowledge stores which issue the detail commands to the various unit controls.

Finally, developments in the computer field already indicate the possibility of providing automatic control systems which will learn. That is, observe results, analyse, and modify the information stored in the memory to improve the performance.

CONCLUSION

It has been mainly single process units, of course, that have been referred to. But the reasoning followed applies equally to the next stage in the chain of command and control, which is the co-ordination of several process units, and in fact the control of the whole plant. That systems will be developed which will enable these stages to be taken over by control systems is certain. That they will be in such a form as to be sufficiently reliable and economic may not seem so certain, and statements similar to that of 1909 referred to in the Introduction will undoubtedly be heard many times. When, however, it is remembered how much has been achieved there can be no doubt that suitable systems will be developed, and that they will justify the considerable effort that both user and manufacturer are already putting into, and will continue to put into, their development.

This future development will have a very important aspect to it : the co-ordination of several engineering and administrative activities, which so far it has been possible to allow to proceed separately to a very large extent. In future there will be an increasing need to carry out the mechanical and electrical engineering and the production organisation as a single system. Only by the close co-operation of manufacturer and user, and designer and operator, will the full benefits that control system development offers be obtained.

ACKNOWLEDGMENTS

The authors wish to thank their colleagues in the Company for their generous assistance in the preparation of this paper, and the South African Institute of Electrical Engineers for permission to reproduce it in this journal.

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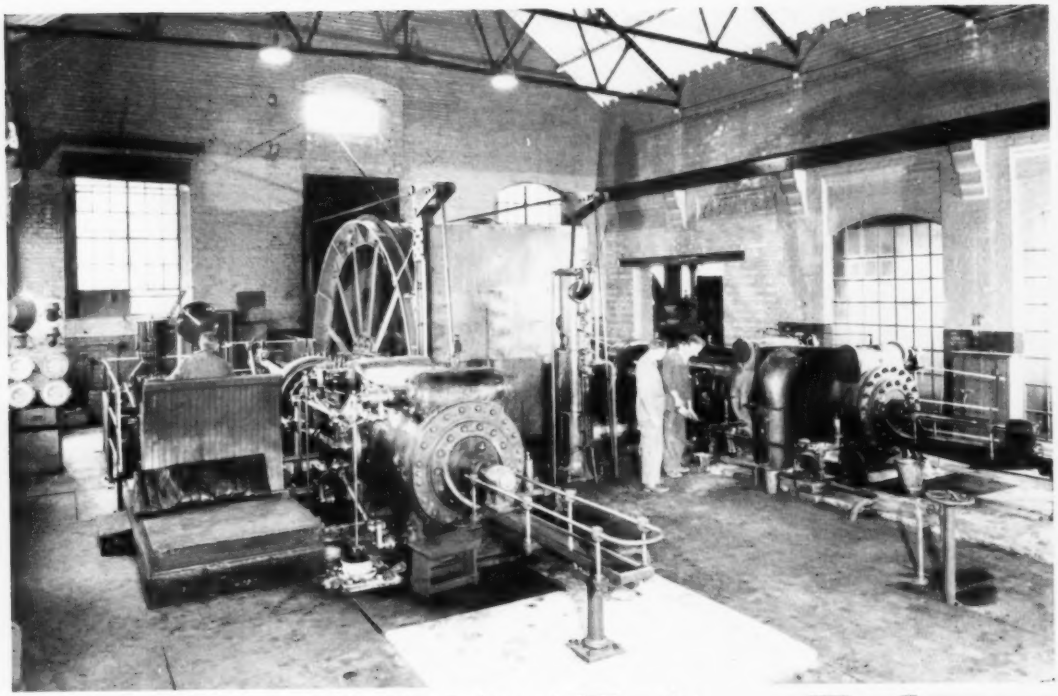


Changeover from Steam to Electric Winding at the Ackworth shaft of Ackton Hall Colliery

by J. ELLIS, Grad.I.E.E., Mining Division

ELECTRICAL SUPPLY being readily available from the grid, The National Coal Board has replaced most steam winders by electrically driven ones. This of course renders it unnecessary to retain steam raising plant at individual collieries, which is expensive to maintain and costly to replace. A recent example of this trend was the order received by the Company for an electric winder to replace an existing steam winder at Ackworth Shaft, Ackton Hall Colliery, Nr. Pontefract, Yorkshire, the subcontractors for the mechanical parts being Messrs. M. B. Wild & Co. Ltd. of Birmingham. All the electrical equipment for the winder was supplied by The English Electric Company. This equipment was installed during 1959, and has been in operation from 5th August of that year.

The Ackworth shaft is situated approximately 1½ miles from the Warren House and Haigh Moor shafts, where the coal is raised and prepared for sale. Fig. 2 shows the layout of the site with the steam winder still operating, and Fig. 4 gives details of the shaft arrangement. The winder serving this shaft is used mainly for winding the men who work the coal seams, and some materials. The two main seams are Silkstone and Warren House, and Table I gives some details of these.

TABLE I

	Silkstone	Warren House
Thickness of seam ..	45 in.	48 in.
Depth below surface..	1,962 ft	1,371 ft
Approximate output of run-of-mine coal per day	1,125 tons	1,440 tons
Men underground per twenty-four hours ..	544	606

Fig. 2.—A view of the Ackworth shaft during steam working

Fig. 1 (Opposite)—From steam to electric drive. The transformation in the winding house of the Ackworth shaft of Ackton Hall colliery, resulting from conversion to electric winding

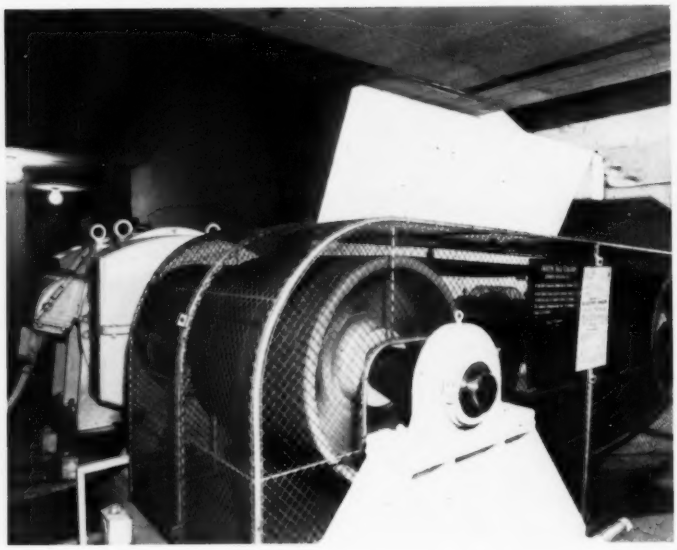


Fig. 3.—The main ventilating fan drive

Thus, over a period of twenty-four hours 1,150 men extract the coal from the seams and descend and ascend by means of the Ackworth shaft winder.

This is the upcast shaft, and all the ventilating air is drawn through the workings by the fan installation whose outlet can be seen in the foreground of Fig. 2. This comprises a 600 h.p. synchronous induction motor and control gear of 'English Electric' manufacture, driving a 100" dia. axial-flow type fan, capable of extracting 228,000 cu ft of air per minute. The motor and belt drive are shown in Fig. 3.

THE STEAM PLANT

When the steam winder was still operating, three Lancashire boilers supplied the winder, baths, and other services. One boiler was fifty years old, and the other two were only three years younger. It was obvious that these could not continue much longer.

To operate the boilers required the services of three boiler firemen and one fitter. During the course of a year, the boilers consumed approximately 3,250 tons of various grades of coal, worth nearly £9,000. As no coal was raised at this shaft it had to be carried by lorry 1½ miles, and a lorry driver and his mate spent two complete days every week transporting the necessary fuel.

The Winder

The shaft was sunk during the period 1910 to 1913, and the Bradley and Craven steam engine was installed in 1914. Fig. 1 shows its layout. The twin horizontal cylinders were 30" bore and 60" stroke, and the pistons were coupled through

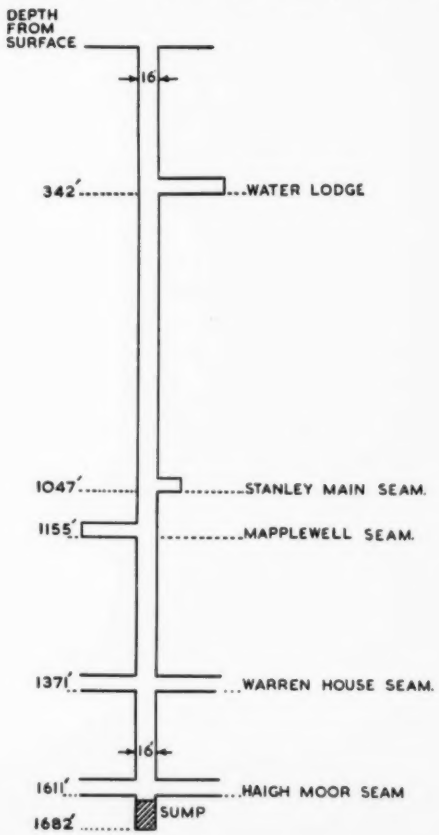


Fig. 4.—The layout of the Ackworth shaft

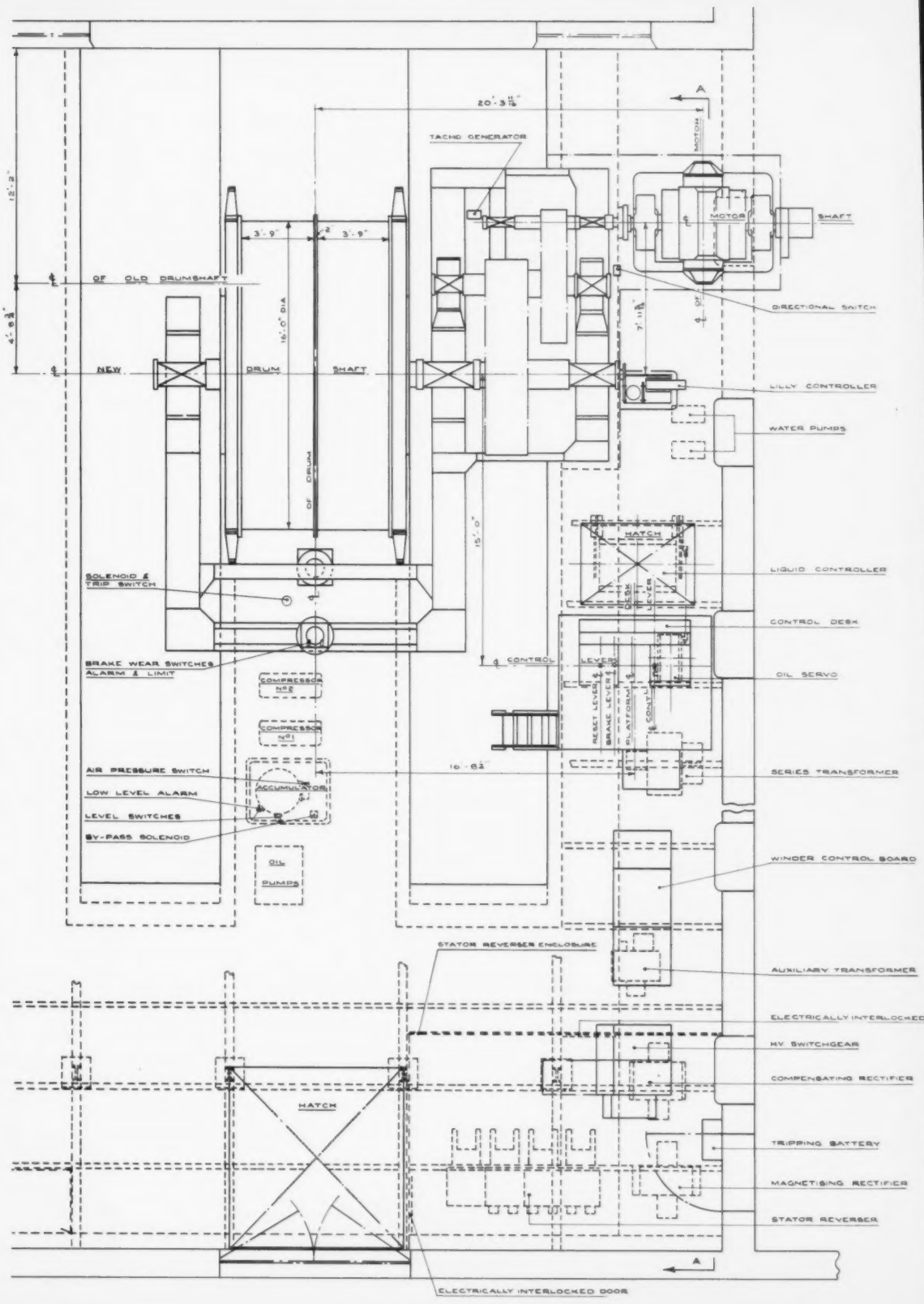


Fig. 5(a).—*Layout of the winder and its associated equipment*

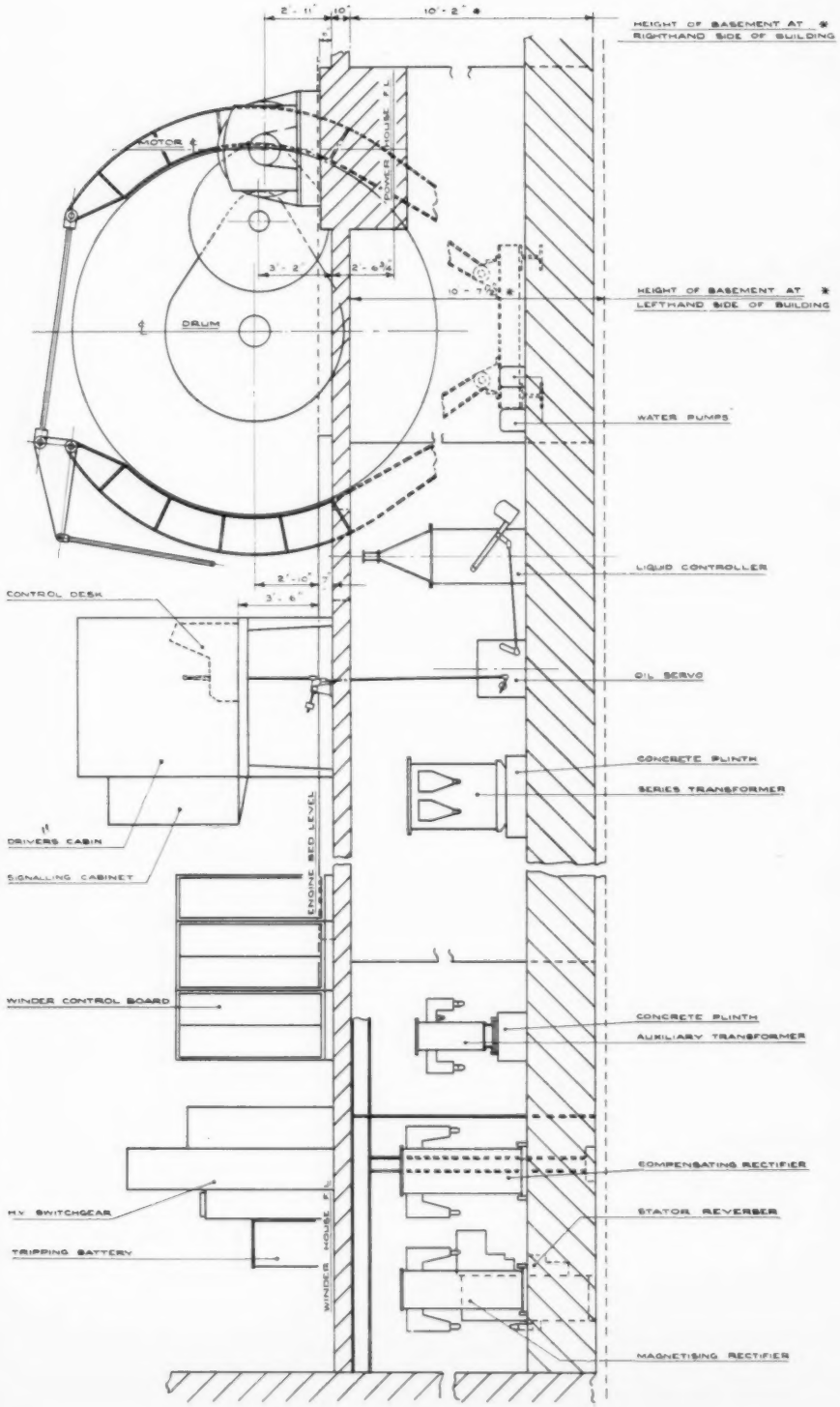


Fig. 5(b).—Section on A-A of Fig. 5(a)

KEY

F.L. = floor level

connecting rods to each end of the drum shaft. This shaft carried a 17′ dia. winding drum. The pistons operated at 120 lb. per sq. in. pressure, controlled by Corliss inlet and exhaust valves.

The driver controlled the throttle and brakes from his position on the left hand side of the drum. The winder was of the cage and counterweight type and the position of the cage was indicated on a round dial-type indicator. For accurate positioning at the landings the driver relied on marks at the outer edge of the drum. Signals were shown on the indicators to the left of the driver.

All this existing equipment was to be removed and replaced by the new electric winder.

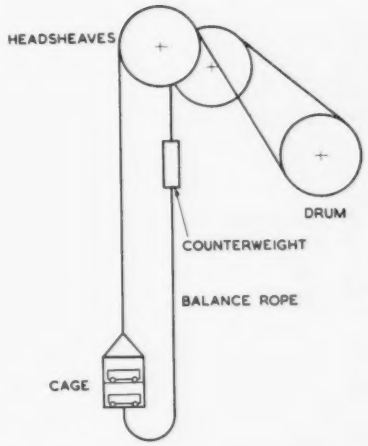


Fig. 6.—The winding arrangement

THE ELECTRIC WINDER DESIGN

As will be seen from Fig. 4, the shaft depth is 1,611 ft. The Silkstone seam is 351 ft deeper, and is reached by means of a drift. It is possible that at some future date the shaft may be deepened this much, giving a shaft depth of 1,962 ft. To provide for this, it was decided to base the new winder design on winding men, materials, or stone to this level.

The new winder continues using the cage and counterweight system operated with the steam engine. In fact, the same two-deck alloy cage, accommodating twenty-five men per deck, is retained. This is attached to one rope and the counterweight to the other. A balance rope, of equal weight to the winding ropes, is suspended from the conveyance and counterweight, so that at no stage of the wind is there any out-of-balance rope. (Fig. 6).

The stone-raising duty to be catered for was the raising of 5·5 tons of stone in a 1·5-ton mine car. Based on this the motor was determined as 450 h.p. The men and material requirements were covered by this rating. At the chosen rope speed, 250 men could be wound to the deepest level in thirty minutes. Material loads up to 5 tons in weight could also be accommodated.

Mechanical Parts

The winder has a single drum, 16′ dia. × 7′ 8″ wide, for coiling two $1\frac{1}{2}$″ dia. locked coil ropes each approximately 2,100 ft long. It was necessary to coil the ropes in two layers, so the drum was made with the barrel divided by a centre flange into two compartments 3′ 9″ wide. At the end of the first layer the rope is turned back on itself for the second layer. To assist the coiling, parallel grooves were turned on the drum barrel.

This design of drum was influenced by the fact that it had to fit the existing foundations, and the centre flange could only be 2″ thick. In order to provide sufficient stability for this flange against the side thrust of the ropes, it was allied to a cast iron centre spider made in halves, keyed to the drum shaft midway between the two conventional drum sides. A ledge was provided on each side of the spider to which were bolted the drum plates.

The brake posts, of the caliper type, were the largest M. B. Wild had so far manufactured. As can be seen in Fig. 5, the posts move about pivots fitted at the lower extremities. Two pairs of brake posts operate on 8″-wide brake rings fixed to each side of the drum. Brake operation is by means of oil using Wild's standard air/oil system. In this the oil for the brake engines is kept at the required pressure in an accumulator by air from a compressor unit.

Electrical Equipment

The National Coal Board Regulations require

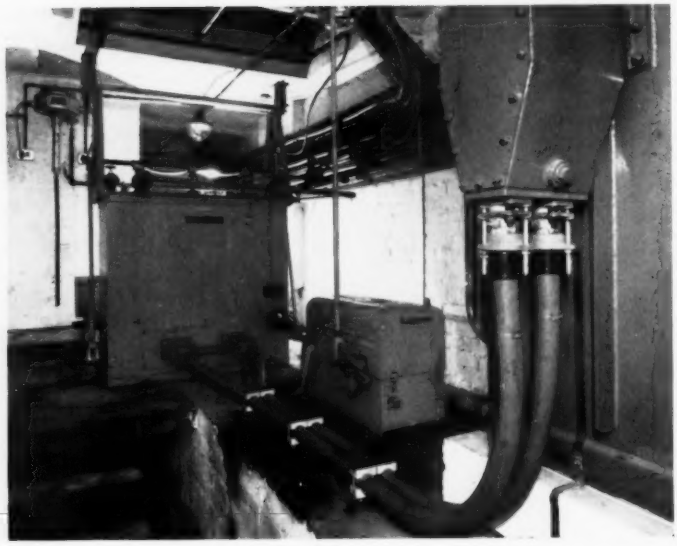


Fig. 7.—A view in the winding house basement, showing the liquid controller, oil servo device, and cables to the series transformer

that any stage of gear reduction should not exceed 10:1. With the rope speed fixed at 20 ft/sec it was found necessary to use double reduction gears with the 570 r.p.m. slipring induction motor. The motor and gears were designed to give a peak output of 900 h.p., over a voltage range of 3,100/3,300 V.

The physical arrangement of the equipment decided on is shown in Fig. 5. Speed control is by means of a servo-operated liquid controller. The arrangement of the linkages from the desk to this equipment, which is mounted in the basement, can be seen in Fig. 7. Motor reversal is achieved by a type 52FH stator reverser located in a locked enclosure in the basement.

THE CHANGEOVER

The changeover was scheduled to take place during the first seven days of the fourteen-day colliery shutdown in July 1959. While most of the electrical equipment could be installed prior to the shutdown, removal of the steam winder and fitting of the new mechanical parts, testing, and commissioning, was scheduled for the seven-day period. Obviously all the equipment had to be available at site in advance of the changeover. Any delay could result in a considerable loss of output from the colliery.

Table II shows the times expected to be taken. It will be seen that the job was to be completed on the 2nd August.

On the electrical side nearly all the installation and cabling was completed prior to the shutdown. Some of the steam pipes were in the way of the cabling, but it was found possible to modify these to enable the cable runs to be completed. To enable the winder motor to be fitted, a space had to be made through the side wall (Fig. 8). The foundation block was cast and the motor fitted in place while the steam winder was operating. The motor was run and the stator reverser contacts proved at this stage.

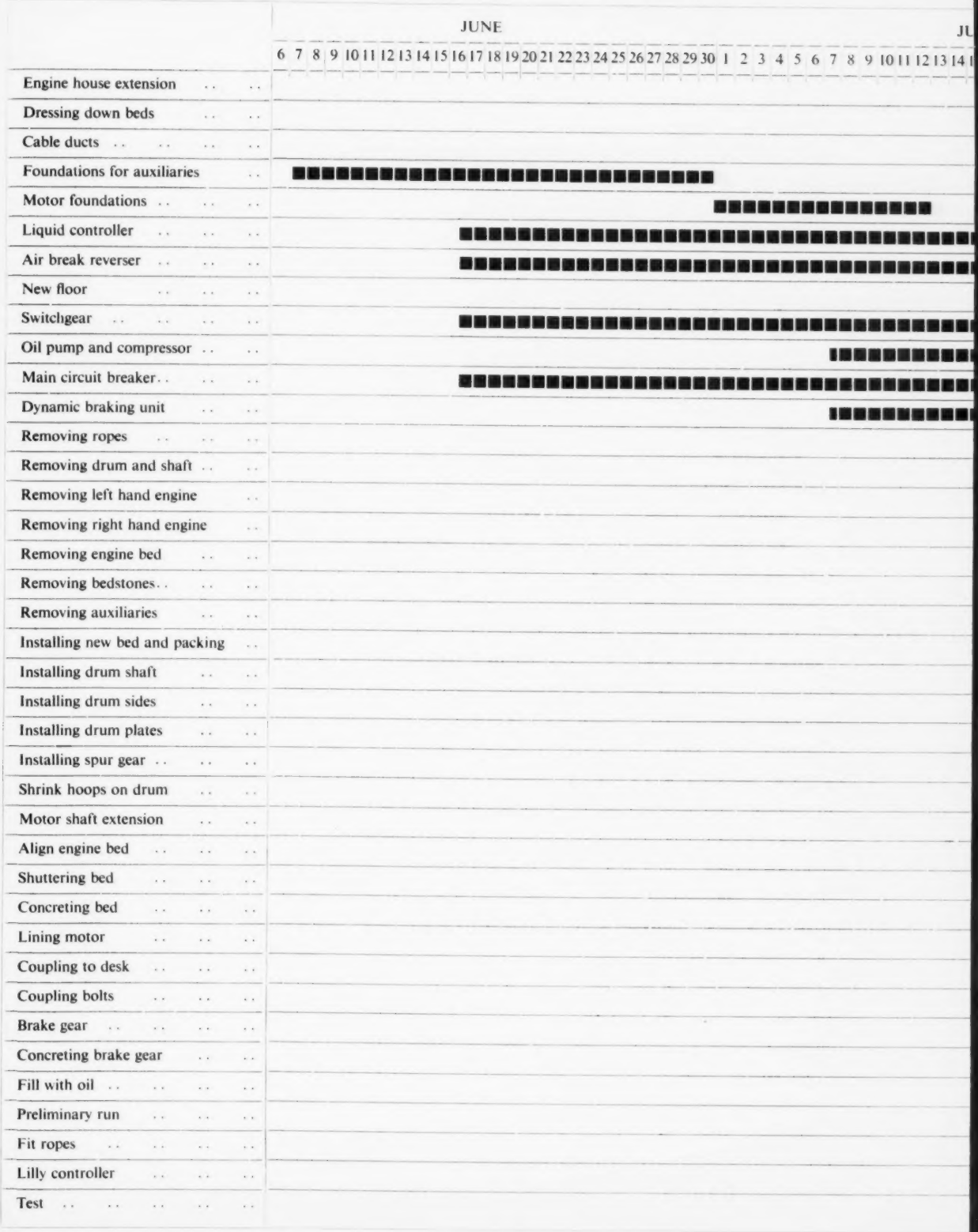
The steam winder became available for dismantling on Saturday 25th July. The winding ropes were immediately removed and work commenced on dismantling the winder. A 10-ton crane was available in the winder house. This was a mechanical type, which had been converted to electrical operation. During the changeover it was run almost continuously, and the only serious hold-ups were due to occasional breakdowns of the crane.

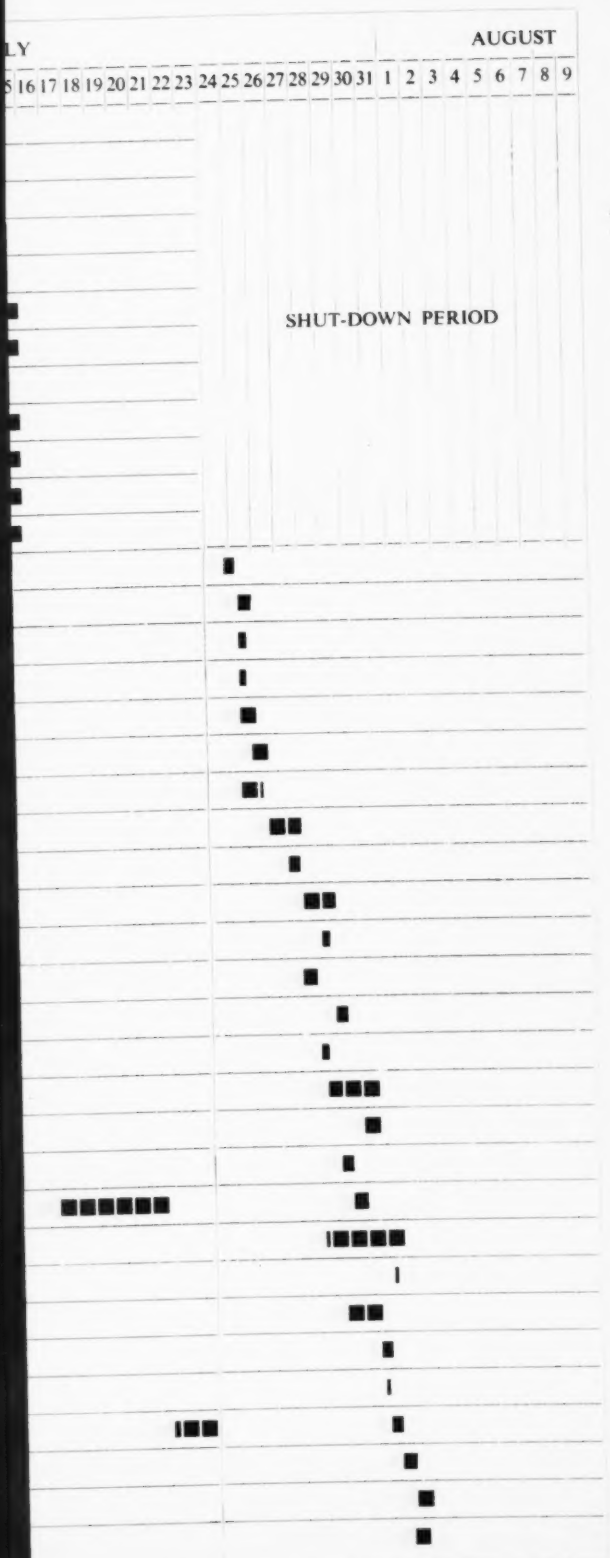
To carry out the installation The English Electric Company and M. B. Wild each provided a supervisor. A staff of three worked under each supervisor. Two shifts of twelve hours were worked during the actual changeover.

The mechanical parts had been designed to fit the plinths carrying the steam winder. It was possible to use seven of the existing holding-down bolts, which saved a considerable amount of time. Holes had to be cut in the blocks for the remainder.

The installation proceeded smoothly. Some delay on the civil construction was encountered in the grouting-in of the motor after the final align-

TABLE II


JUNE
JU
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Engine house extension
Dressing down beds
Cable ducts
Foundations for auxiliaries
Motor foundations
Liquid controller
Air break reverser
New floor
Switchgear
Oil pump and compressor
Main circuit breaker
Dynamic braking unit
Removing ropes
Removing drum and shaft
Removing left hand engine
Removing right hand engine
Removing engine bed
Removing bedstones
Removing auxiliaries
Installing new bed and packing
Installing drum shaft
Installing drum sides
Installing drum plates
Installing spur gear
Shrink hoops on drum
Motor shaft extension
Align engine bed
Shuttering bed
Concreting bed
Lining motor
Coupling to desk
Coupling bolts
Brake gear
Concreting brake gear
Fill with oil
Preliminary run
Fit ropes
Lilly controller
Test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AUGUST
5 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9
SHUT-DOWN PERIOD

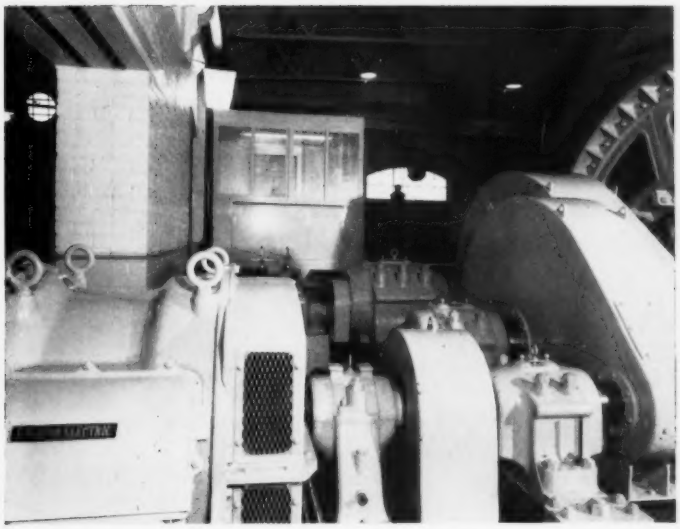


Fig. 8.—The driving motor and gear unit. The driver's control cabin can be seen in the background

ment, but the equipment was in operational order on 5th August.

Apart from minor 'teething troubles' the equipment has been in continuous operation since its installation.

THE NEW WINDER

The driver is now housed in a comfortable cabin to the right of the winder. At the back of the cabin is a cubicle containing the new shaft signalling equipment, which operates the indicators mounted on the neat control desk shown on p. 27.

At the centre of the desk is the latest 'English Electric' miniature type depth indicator, which shows the situation of the cage at any instant, and enables the driver to position at the landings without any reference to marks on the drum. It comprises a circular dial with a narrow annulus, representing the drum cheek, and a pointer representing the conveyance. Any mark on the annular dial completes one revolution for each revolution of the drum, while the pointer moves a few degrees only. The pointer is transparent, and is marked with a radial line. The pointer and annulus marks coincide at intervals of just over one revolution of the drum, and their combined use permits accurate determination of the conveyance position. Three lamps mounted behind the dial provide adequate illumination without glare.

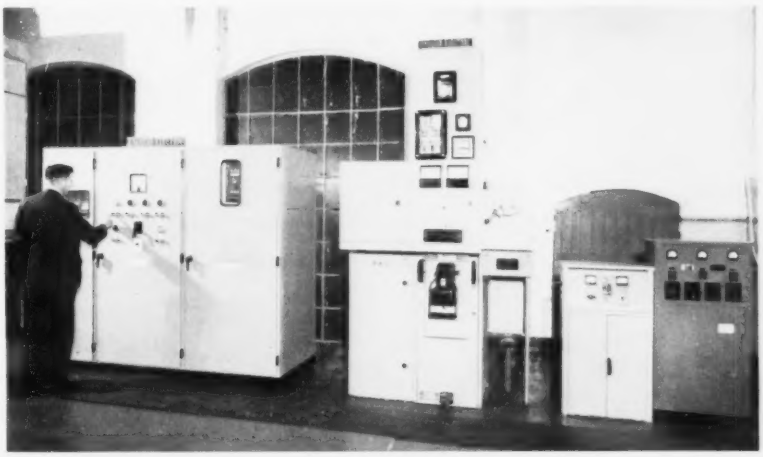
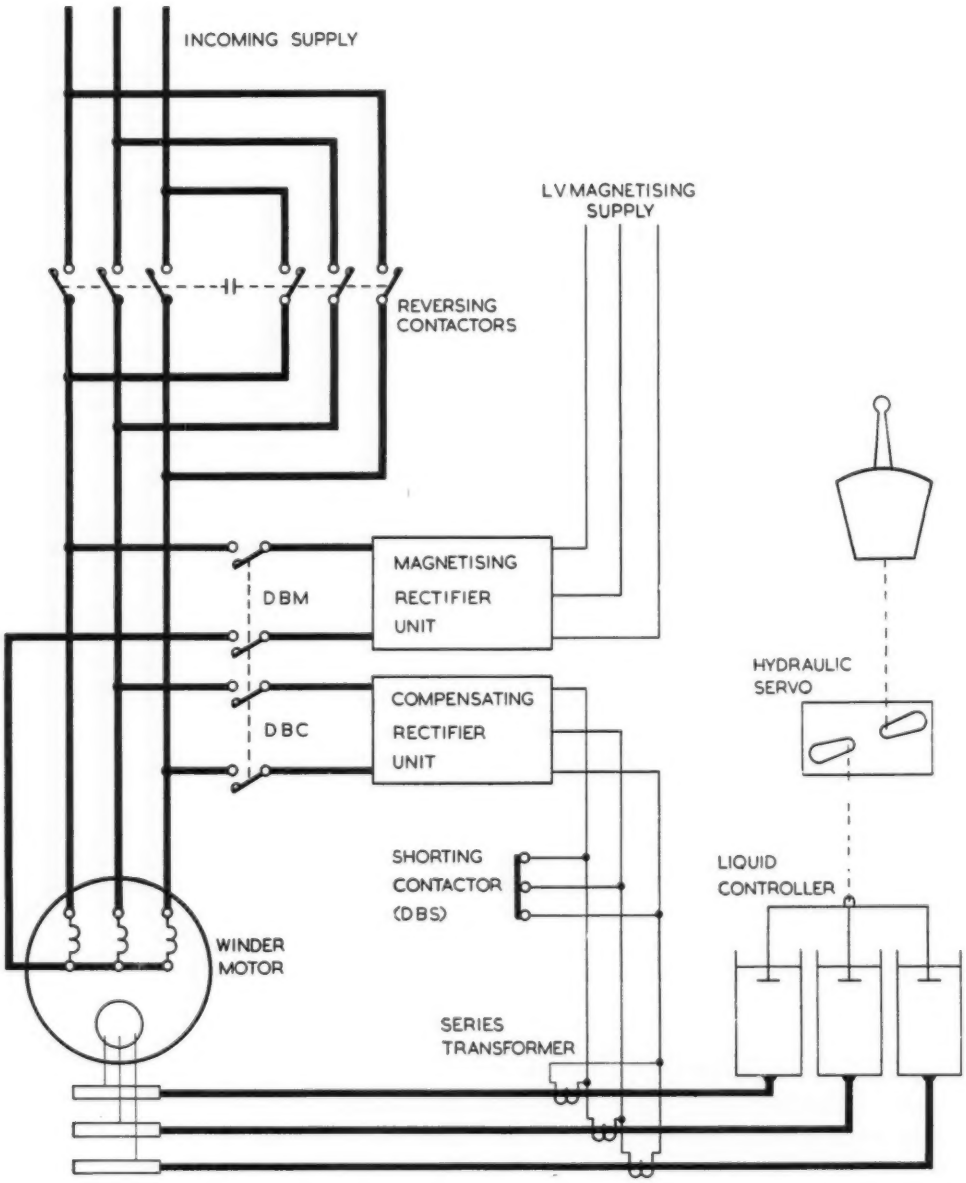


Fig. 9.—The auxiliary switchboard and main switchgear. These are located in the winding house, behind the driver's control cabin



D.B.M. = dynamic braking magnetising contactor D.B.C. = dynamic braking compensating contactor
D.B.S. = dynamic braking shorting contactor

Fig. 10.—Schematic diagram of the dynamic braking system

Dynamic Braking

During normal winding the cage is loaded more heavily than the counterweight, and positive power is required from the winder motor. The driver is able to control the speed by means of the liquid controller—the setting of which corresponds to the position of his control lever—and by means of the mechanical brakes. However, for certain winds, such as when a light or empty cage is raised or a heavy load is lowered, the descending out-of-balance load is such that it will drive the motor, and braking must be applied to the system. The mechanical brakes could be used, of course, but this would lead to excessive wear of the brake linings. Electrical braking by plugging is also possible, but requires appreciable energy from the supply and increases wear on the reversing contactors. However, the driver has available the 'English Electric' dynamic braking system, to give him the necessary control for just such a wind.

This system is shown in block form in Fig. 10. The driver's controller is provided with an 'h' slot, and moving the lever into the small arm applies dynamic braking. This disconnects the winder motor from the supply by opening the reversing contactors, and energises one phase of the stator from a small steady d.c. supply. A magnetic field is created in which the rotor is driven by the descending load, and the machine acts as an alternator loaded on the rotor resistance. The value of the rotor current is determined by the setting of the liquid controller.

A three-phase series transformer is inserted in the rotor circuit, and rectified current from this is fed to the other two phases of the motor stator. This compensates for the de-magnetising effect of the rotor current, and the motor then becomes a self-compensated alternator. The amount of braking applied can be adjusted by the driver, by moving his lever in the dynamic braking slot, adjusting the resistance of the liquid controller. This system, using entirely static apparatus, was first introduced by The English Electric Company in 1937. It enables the driver to control the speed of the winder right down to a creep speed, when the mechanical brakes must be applied for final stopping. It is very smooth in operation, saves considerable wear of the brake linings, and consumes only a very small amount of energy from the supply.

THE NATIONAL COAL BOARD has achieved considerable saving by installing the electric winder. The outlay on maintaining and operating the steam plant was considerable. Electricity is now bought from the supply authority at a cost of approximately 1·1d. per kWh unit.

The winder is a much neater and cleaner installation, as can be seen from Fig. 1, and the driver's job is less fatiguing.

While this is a relatively small installation, it is typical of the many larger winders which have been installed by The English Electric Company, both in this country and overseas. These provide safe access to the workings for men, and during the course of a year raise to the surface millions of tons of raw material.

ACKNOWLEDGMENTS

The author wishes to thank the National Coal Board for permission to publish this article.

Ingot Buggy and Shuttle Car Scheme at the Port Talbot Works of The Steel Company of Wales

by R. B. LARKINSON, M.A.(Oxon.), A.M.I.E.E., Engineering Section (Servo), Metal Industries Division.

A description of the method of control for cars transferring ingots from soaking pits to slabbing mill.

THREE YEARS AGO it was decided to increase the slab producing capacity of the Port Talbot works of The Steel Company of Wales. In order to do this a vertical edger was to be added to the existing slabbing mill, and other equipment was to be enlarged. The average weekly output of the slabbing mill was expected to go up by nearly 60% and in order that there should be sufficient ingots ready to feed to it, the number of soaking pits was to be increased. It only remained to speed up the rate of transfer of ingots from the soaking pits to the slabbing mill. This was achieved by the means described in this article.

THE ORIGINAL SCHEME

The existing method of feeding the mill was by means of an ingot buggy running at 800 f.p.m. on a 10 ft gauge track beside the soaking pits. The buggy, which weighed 130 tons empty, had mounted on it four motors, which received their supply from eleven pick-up rails mounted alongside the track. One of the motors tilted from the vertical to horizontal the bucket mounted on the buggy, into which the soaking pit cranes placed the ingots ; another motor drove the rolls on the buggy, by means of which the ingot was transferred to the

Fig. 1.—The ingot buggy and shuttle car alongside the ingot soaking pits at the Port Talbot steelworks of The Steel Company of Wales. The pick-up rails from which the buggy takes its power can be seen on the left of the shuttle car, set vertically alongside the soaking pits. In the foreground can be seen the railway track used for bringing ingots to the soaking pits.

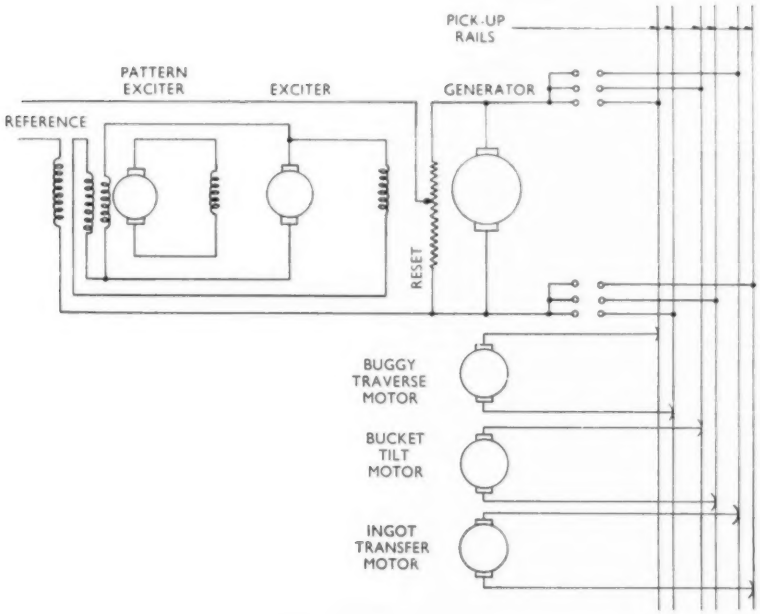


Fig. 2. — The ingot buggy control system. (Only one of the two traverse motors is shown)

mill receiving tables ; the two remaining motors drove the ingot car up and down the 800 ft track.

The supply to the pick-up rails came from two generators whose excitation was provided by an exciter and a pattern exciter. On a control field of the latter there was voltage mixing of the reference and the reset (Fig. 2). The generator outputs could be switched on to different pick-up rails to feed the different motors for tilting, transferring and traversing. The buggy was operated manually.

THE NEW SCHEME

The layout of the new scheme, which was supplied by The English Electric Company, is shown in Fig. 3. From this and Fig. 1 it can be seen that there was no possibility of installing another track on which a second ingot buggy could run and feed the mill simultaneously with the first one, since the only approach to the mill was taken up by the existing buggy track and the railway lines on which the ingots are brought to the soaking pits. It was decided therefore to have a shuttle car running

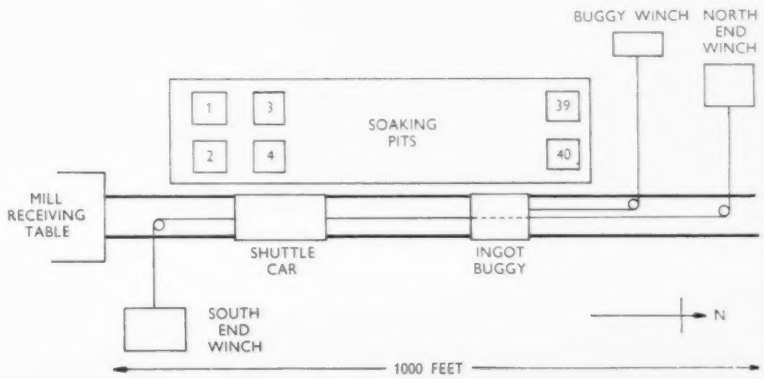


Fig. 3.—Layout of the shuttle car hauling equipment and ingot buggy positioning device

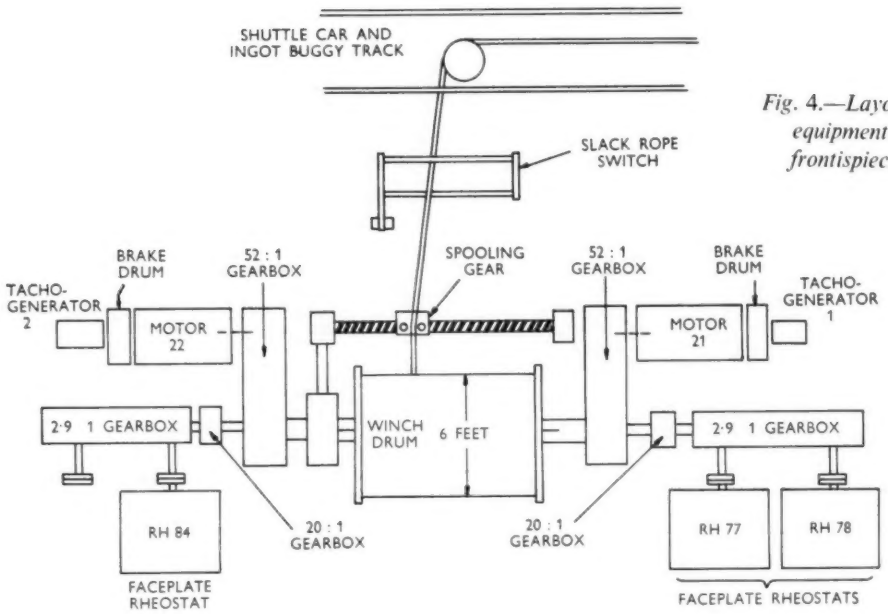


Fig. 4.—Layout of the winch equipment shown in the frontispiece of this issue

at a speed of 1,000 f.p.m. on the same track as the buggy. This shuttle car was to carry two ingots and transfer them to the mill while the ingot buggy was receiving a further ingot into its bucket and tilting it to the horizontal position. Since the eleven pick-up rails and photo cell equipment occupied most of the space alongside the track, the motive force for the shuttle car could not come from pick-up rails. It was decided, therefore, to make the shuttle car rope hauled.

Shuttle Car Hauling Equipment

The layout of the hauling equipment is shown in Fig. 3 and consists of two 6 ft dia winches each having a total inertia of 33 tons-ft², with their associated spooling gear, slack rope switches and gearboxes at both ends of the track. The south end winch equipment is shown in detail in Fig. 4.

Round each winch is 1,000 ft of 1¼ in dia cable having a total weight of 1 ton. Each winch is driven by two 200 h.p. 460 V mill type motors through a 52 : 1 gearbox.

The electrical power circuits for the south end winch are shown in Fig. 5, the north end winch being a duplicate. The motors are arranged in series sandwich with two 460V generators, and provision is made also for two motor-one generator and one motor-one generator operation by means of the changeover switches shown in Fig. 6. The generator fields are fed from control exciters which receive their excitation from push-pull magnetic amplifiers.

Transfer of Ingots from Buggy to Shuttle Car

The shuttle car is loaded in the following manner. An ingot is lowered by crane into the buggy bucket, the bucket is tilted to the horizontal position and the rolls of both shuttle car and ingot buggy are operated simultaneously to transfer the ingot to the shuttle car. The buggy bucket is tilted back to the vertical position to receive a further ingot, (Fig. 7), and is again tilted to the horizontal position, when the first ingot is rolled backwards towards the second until they are nose-to-tail ; then by operating the two table rollers together the two ingots are transferred to the shuttle car.

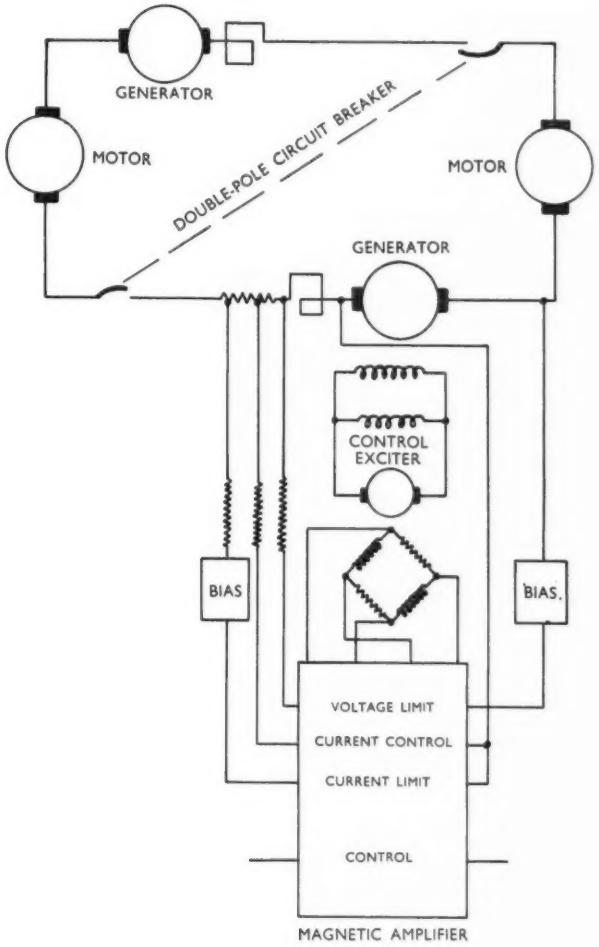


Fig. 5.—The electrical power circuit for the winch equipment

Main Requirements for new Scheme

The main requirements of the scheme were :—

1. Automatic position control of the shuttle car at twenty pit positions along the track, and at the slabbing mill approach table.

2. Automatic position control of the ingot buggy at these twenty-one positions, using the existing speed control equipment.

3. Acceleration and deceleration times of the shuttle car to be twelve seconds.

4. The shuttle car to exert a pressure on the buggy and on the mill approach table when it is in contact with either. This is necessary in order to keep the shuttle car stationary when receiving or transferring ingots.

5. The operators to be able simultaneously to select positions for the ingot buggy on the other side of the shuttle car, and *vice versa*, without it resulting in a collision at speed.

6. The ropes to be kept taut all the time ; i.e. there should be a definite minimum tension in the rope.

7. Positioning to be accurate to within two feet over the 1,000 ft of travel.

8. The scheme to be interlocked so that (*a*) the operator cannot work either the buggy tilt or the buggy transfer unless the shuttle car be in contact with it, (*b*) the shuttle car rolls cannot work unless the car be either at the buggy or at the mill (Fig. 8).

Control of Shuttle Car

The required behaviour of the currents in the Ward-Leonard loops during a run are as shown in Fig. 9. Before moving off, the two ropes are kept taut by a minimum tension current. When movement is required, the Ward-Leonard loop controlling the appropriate winch takes twice full load current, and this current drops to a value necessary to keep the car moving at full speed when this has been reached. When the car is the correct distance away from its stopping point the other Ward-Leonard loop takes twice full load current until the car stops, the first loop taking sufficient current to provide the minimum tension only.

It was decided that the best method of obtaining these characteristics was to have three feedbacks : current control, current limit, and voltage limit. These would allow the characteristics to be obtained by (*a*) permanently feeding a small control signal into the magnetic amplifier which, in combination with the current control feedback, would give a minimum tension current in each Ward-Leonard

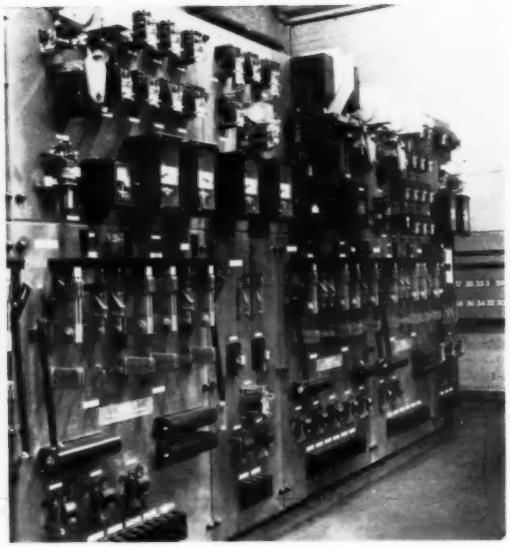


Fig. 6.—Shuttle car control board and position indicator

loop ; (*b*) feeding a signal into the magnetic amplifier which would be opposed by the current control and current limit feedbacks when the drive was accelerating, and by the voltage limit circuit when the drive reached top speed ; and (*c*) changing over the signal to the magnetic amplifier controlling the other Ward-Leonard loop when the position was reached at which deceleration should commence.

The signal (*a*) for each loop is obtained from a resistance network across a constant voltage exciter. The signal (*b*) is obtained from the difference of position error signal and a speed feedback signal from a tacho-generator, which gives the necessary changeover in (*c*).

Since it is necessary that a large position error and a small position error give the same acceleration rates, a limit circuit has to be employed, and the behaviour of the various inputs and feedbacks is as shown in Fig. 10.

Position Indication Devices

For detecting the position of the shuttle car the pick-up arm of a 331-way faceplate rheostat connected across the c.v.e. is driven from the south end winch through a 58 : 1 reduction gearbox with a backlash of less than 30 minutes on the output side. Thus each step on the rheostat corresponds to 3·036 ft of travel of the shuttle car.

To detect the position of the ingot buggy there is a 3 ft dia small winch at the north end of the track (Fig. 3) round which passes a $\frac{3}{8}$ in dia rope. The rope is attached to the ingot buggy and is either pulled out by the buggy when it travels towards the mill, or is wound in by a small motor which drives the winch when the buggy travels away from the mill. From the winch through a 116 : 1 gearbox are driven the arms of three other 331-way face

Fig. 7.—The shuttle car and ingot buggy alongside the ingot soaking pits. The car is being loaded with two ingots by means of the buggy

Fig. 8.—Ingots being transferred on to the slabbing mill table from the shuttle car

plate rheostats, the voltage on the arm of one being an indication of the ingot buggy positions.

Position Reference Devices

The position reference voltage for the shuttle car is obtained from two faceplate rheostats connected as in Fig. 11. The rheostats RH82 and RH83 are mounted on the ingot buggy winch and have their arms driven from the winch through the same 116 : 1 gearbox as RH79. The two rheostats RH77 and RH78 from which the ingot buggy position reference is obtained are mounted at the south end winch of the shuttle car, which drives their pick-up arms through a 58 : 1 gearbox.

The position selector switches S101 to S121 are arranged as shown in the diagram, so that if two switches are depressed at the same time the one which selects a shuttle car position nearer the mill, i.e. further from the buggy, is the one

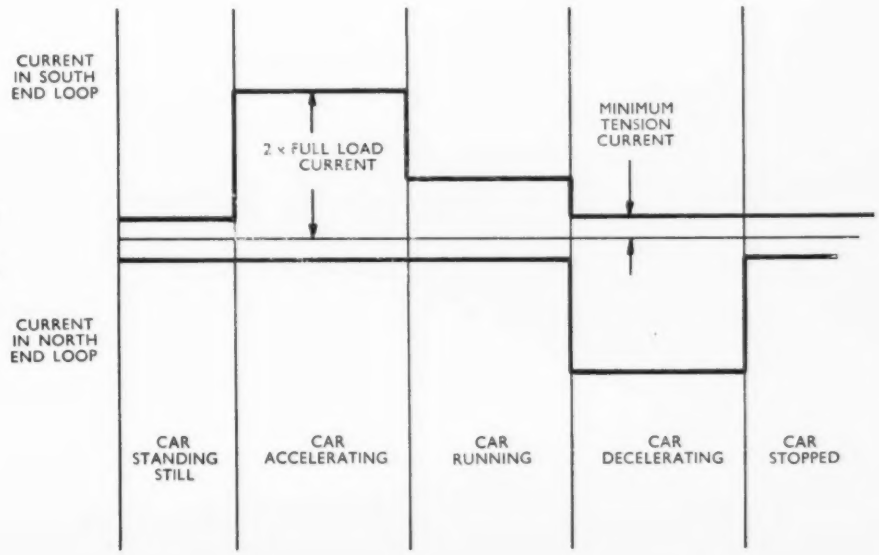


Fig. 9.—Required behaviour of currents in the Ward-Leonard loops during a north-to-south run

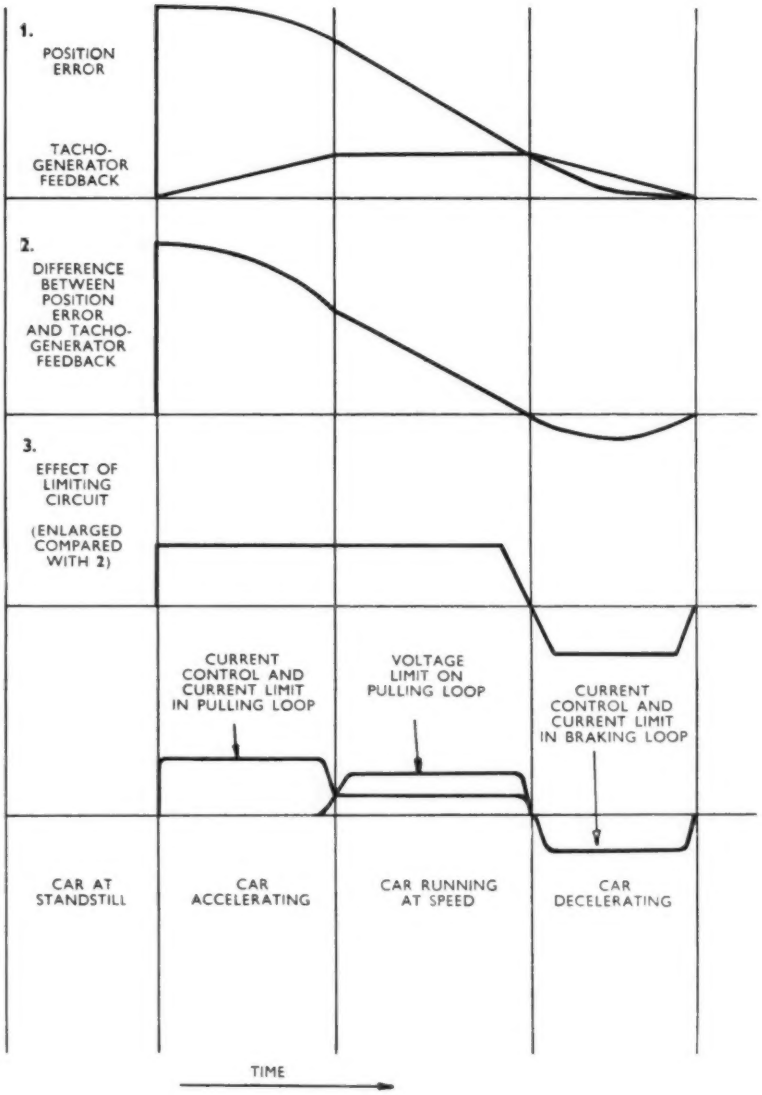


Fig. 10.—*Behaviour of inputs and feedbacks to the magnetic amplifiers*

which is effective. Also, this arrangement prevents all possibility of shorting out a portion of the rheostat. The combination of two faceplate rheostats for position reference sources is such that, if the ingot buggy is at pits 25 and 26, (i.e. the position of moving arms on RH82 and RH83 being as shown), and the selector S121 for the shuttle car is depressed, the effect will be the same as if the switch selecting pits 25 and 26 for the shuttle car had been depressed, and the shuttle car will come to a stop at the buggy.

The position reference rheostats for the buggy are similar, except that the position selection switches are facing the other way.

The ganged rheostats RH80 and RH81, and

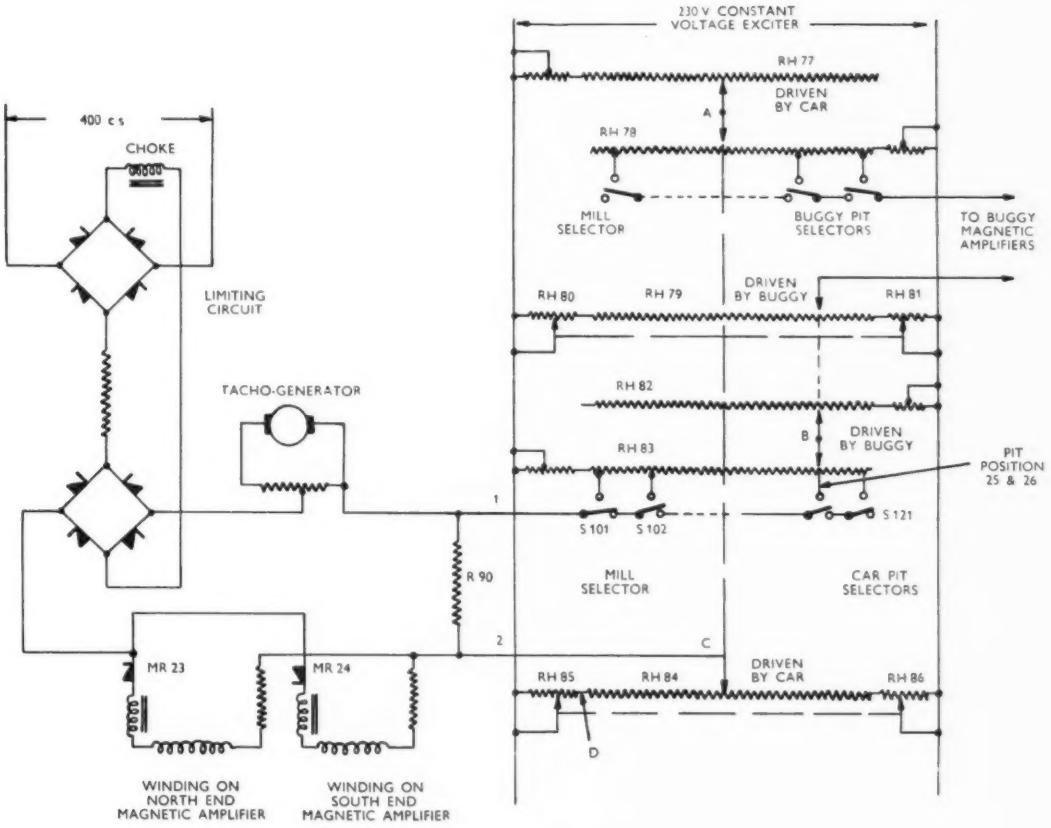


Fig. 11.—Arrangement of position reference and position indication rheostats

RH85 and RH86 are manually adjustable to allow for stretch in the ropes.

Methods of Obtaining Inputs

The manner in which the correct input signals are obtained is illustrated in Fig. 11. The position error signal is impressed across wires 1 and 2, and is opposed by a signal of tachogenerator volts, the resultant being limited by the rectifier circuitry and then, according to the polarity of the resultant signal, it is fed into the magnetic amplifier winding controlling either one Ward-Leonard loop or the other.

In practice two tachogenerators are used, with arrangements for changing from the running to the standby if the running one is faulty, and for sounding an alarm if the standby is faulty.

The resistance R90 across the wires 1 and 2 provides a path for the tachogenerator feedback if the position reference devices go open circuit.

The rectifiers MR23 and MR24 are germanium junction rectifiers, requiring only a very low voltage to pass current in the forward direction.

Ingot Buggy Control

In order to incorporate the existing ingot buggy control system into the 'English Electric' scheme the control field on each pattern exciter was split into two halves. The two main generators are used for feeding the tilting and transferring motors, so it

was necessary to provide a means of changing rapidly from one scheme to the other. This changeover is effected by two relays. In the de-energised position the connections are as in the original scheme. In the energised position the two halves of one field are connected in a resistance bridge across the output of an 'English Electric' push-pull magnetic amplifier and the two halves of the other field are connected in a resistance bridge across another push-pull magnetic amplifier, the feedback of the generator volts being fed into the appropriate magnetic amplifiers.

The position error signal for the buggy is taken from the faceplate rheostats, fed into a limiting circuit and then through the two magnetic amplifier control windings, which are connected in series.

The value of the gain for the voltage feedback loop and the setting of the limiting circuit to provide the correct stopping characteristic for the buggy had to be found by trial and error during commissioning.

Ingot Buggy Winch Control

The motor driving the ingot buggy winch is fed from a generator whose fields are fed from a push-pull magnetic amplifier. There is a simple current control with two input signals to the magnetic amplifier. One provides a tension in the rope when the buggy is standing still, the other provides an even greater current when the buggy is moving. There is only one feedback which is proportional to current. The generator volts therefore adapt themselves to the value required to give the current demanded and the rope is thus kept continually taut.

Other Controls for the Shuttle Car

Besides the automatic control for the shuttle car there is provision for working it manually and for inching it along the track. The hand controller has three speeds, the first two being obtained from a resistance network across the constant voltage exciter; the top speed signal is taken between the points A and B in Fig. 11 thereby decreasing the top speed value as the ingot buggy and shuttle car come together. When this happens the first two speeds are decreased by a fixed amount also. The hand signal is fed into the two wires, 1 and 2, via a suitable changeover switch, when manual control is required. When inching of the shuttle car is required the minimum tension signal into the magnetic amplifier controlling the appropriate Ward-Leonard loop is increased. This produces a state of out-of-balance in the tensions, and the shuttle car moves slowly in either one direction or the other.

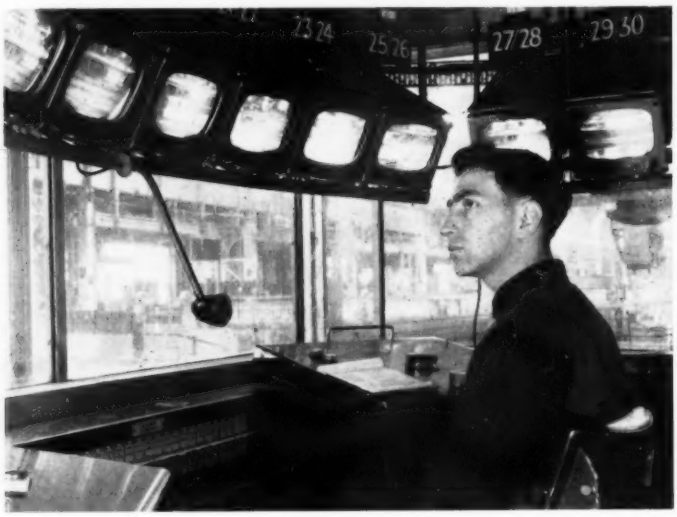


Fig. 12.—The operator's control cabin, showing the television receivers and position selectors (lower left)

The local winch control which uses the same magnetic amplifier winding is the one which comes from pistol grip switches mounted near each winch. By means of these switches signals of either polarity can be fed into the magnetic amplifiers controlling their respective winches, so that the winch will either wind in or pay out the rope. At the same time a lower voltage limit is applied, and in consequence the winch rotates at 10% full speed. This control is used when the ropes on the winches have to be changed.

The shuttle car can take two twenty-ton ingots with approximately five feet to spare, or three

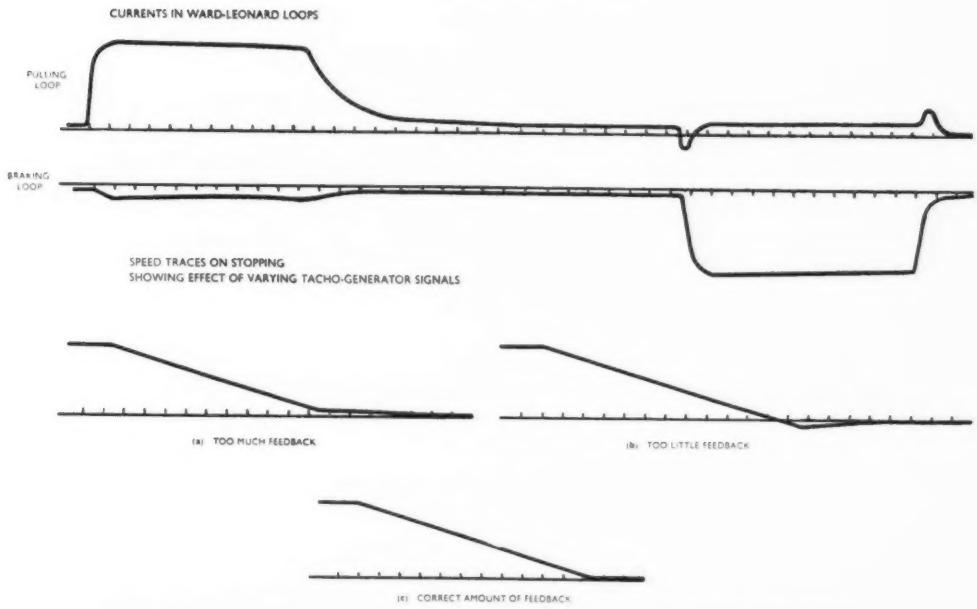


Fig. 13.—Traces from the analogue study on which the system was based

eleven-ton ingots. Originally, disappearing stops were mounted on the shuttle car, so that the north end stop was raised unless a mechanism was operated by a protruding finger mounted on the buggy, and the south end stop was raised unless operated by a protruding finger at the mill. These stops were removed because of difficulty with ingot scale.

The operator is housed in a separate cabin (Fig. 12). To assist him, sixteen television cameras are mounted opposite the soaking pits and sixteen receivers are arranged in a circle just above eye level in the cabin. This provides a continuous picture of the track and enables the operator to see that the control which causes the shuttle car to press up against the buggy is working satisfactorily. The equipment was supplied by Marconi's Wireless Telegraph Company Ltd.

Also mounted in the operator's cabin are two selsyn receivers with concentric spindles for the indicating arms. These indicate on a circular scale the positions of the buggy and car on the track. The selsyn transmitters are driven from the winches.

When the car and buggy are together the potential between points A and B on Fig. 11 is zero, and thus proximity is detected by a moving coil relay connected between these two points. The relay operates a signal to the magnetic amplifier controlling the north end winch, which consequently pulls the shuttle car up to the buggy. Similarly when the car is at the mill the potential between points C and D in Fig. 11 is zero, and a moving coil relay connected between them drops off, and the south end winch receives a signal pulling the shuttle car firmly up to the mill.

Analogue Computer Study

When the initial design was made for the scheme an analogue was drawn up which was then put on an analogue computer and was found to be unsatisfactory. The scheme was modified and the altered analogue was studied and found to give the required results. Some traces taken from the analogue study are shown (Fig. 13), the main point of interest being the effect of small changes in the tachogenerator feedback. It was found that the scheme in operation behaved in a manner closely corresponding to the analogue.

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